FB-00-02

DEPARTMENT OF THE NAVY
NAVAL AIR SYSTEMS COMMAND
NAVAL AIR SYSTEMS COMMAND HEADQUARTERS
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NAVAIRWARCENACDIVTRENTON-LR-PPE-97-3

PERFORMANCE EVALUATION OF POTENTIAL FUEL SYSTEM ICING INHIBITORS IN AVIATION JET FUEL USING THE U.S. NAVY AIRCRAFT FUEL SYSTEM ICING SIMULATOR

FINAL REPORT

29 May 1997

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Report Documentation Page		*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE **29 MAY 1997**	2. REPORT TYPE **Research Report**	3. DATES COVERED **01-10-1996 to 30-04-1997**
4. TITLE AND SUBTITLE **PERFORMANCE EVALUATION OF POTENTIAL FUEL SYSTEM ICING**		5a. CONTRACT NUMBER **N/A**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER **N/A**
6. AUTHOR(S) **John Cummings; Douglas Mearns**		5d. PROJECT NUMBER **N/A**
		5e. TASK NUMBER **N/A**
		5f. WORK UNIT NUMBER **N/A**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Air Warfare Center, Aircraft Division, Trenton NJ,Parkway Avenue,Trenton,NJ,20628**		8. PERFORMING ORGANIZATION REPORT NUMBER **NAWCAD-TRN-LR-PPE-97-3**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Naval Air Systems Command, 1421 Jefferson Davis Highway, Arlington, VA, 22243**		10. SPONSOR/MONITOR'S ACRONYM(S) **N/A**
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) **N/A**
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT
The Naval Air Warfare Center, together with the Air Force?s Wright Laboratories, is actively looking for additives which can be used as potential Fuel System Icing Inhibitors (FSII) in military aviation turbine fuels in place of the current standard FSII, Diethylene Glycol Monomethyl Ether (DiEGME). This was started because of concern that DiEGME, as a member of the glycol ether chemical family, might be regulated more stringently, greatly increasing the costs (procurement, disposal, etc.) associated with use of this additive. DiEGME, used by the U.S. Navy for over 20 years, was chosen as the DOD/industry standard FSII when the use of the former standard FSII (Ethylene Glycol Monomethyl Ether or EGME) was stopped due to concerns over safety of use. Current efforts to determine suitable substitute FSII additives are directed in two areas: development of non-environmentally dangerous FSII additives and adaptation of readily available, more environmentally friendly, off-the-shelf compounds to use as FSII additives. FSII is added to military jet fuels for two reasons: to prevent the formation of ice in aircraft fuel systems and to prevent the growth of micro-organisms in fuel tanks (aircraft and bulk storage). References (a) and (b) set down the required specification concentration of FSII in military aviation jet fuel in terms of minimum and maximum allowable additive concentrations (measured in volume percent). EGME, DiEGME and 23 candidate additives were evaluated. Descriptions and chemical structures of each additive are provided in the report.

15. SUBJECT TERMS
FSII; DPG; glycerol formal; DiEGME; icing inhibitor; EGME; ethylene glycol; JP-5; JP-8; experimental additives

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**10**	**44**	

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References.

(a) Military Specification, MIL-T-5624R, Turbine Fuel, Aviation, Grades JP-4, JP-5 and JP5/JP-8 ST
(b) Military Specification, MIL-T-83133E, Turbine Fuel, Aviation, Kerosene Types, NATO F-34 (JP-8) and NATO F-35
(c) NAPC-PE-141C of June 1985
(d) MIL-HDBK-200G, Quality Surveillance Handbook for Fuels, Lubricants and Related Products of July 1987
(e) NAVAIR 00-80T-109, Aircraft Refueling NATOPS Manual of 15 May 1996
(f) U.S. Air Force Technical Order 42B-1-1, Quality Control of Fuels and Lubricants, Change No. 8 of September 1992
(g) DiEthylene Glycol Monomethyl Ether, Glycerol Formal, and DiPropylene Glycol Use, Handing and Disposal, SEMCOR, Inc. of June 1996

Enclosures.

(1) Descriptions of FSII's Evaluated
(2) Schematic of FSIS Test Rig
(3) Description of FSIS Test Protocol
(4) Figures 1 through 24
(5) Curve Fits Used to Graphically Compare Data Sets
(6) Performance Comparison of Successful FSII's/Candidates for Additional Research
(7) Performance Comparison of Candidates Not Selected for Additional Research

1. Introduction.

a. The Naval Air Warfare Center, together with the Air Force's Wright Laboratories, is actively looking for additives which can be used as potential Fuel System Icing Inhibitors (FSII) in military aviation turbine fuels in place of the current standard FSII, Diethylene Glycol Monomethyl Ether (DiEGME). This was started because of concern that DiEGME, as a member of the glycol ether chemical family, might be regulated more stringently, greatly increasing the costs (procurement, disposal, etc.) associated with use of this additive. DiEGME, used by the U.S. Navy for over 20 years, was chosen as the DoD/industry standard FSII when the use of the former standard FSII (Ethylene Glycol Monomethyl Ether or EGME) was stopped

due to concerns over safety of use. Current efforts to determine suitable substitute FSII additives are directed in two areas: development of non-environmentally dangerous FSII additives and adaptation of readily available, more environmentally friendly, off-the-shelf compounds to use as FSII additives.

b. FSII is added to military jet fuels for two reasons: to prevent the formation of ice in aircraft fuel systems and to prevent the growth of micro-organisms in fuel tanks (aircraft and bulk storage). References (a) and (b) set down the required specification concentration of FSII in military aviation jet fuel in terms of minimum and maximum allowable additive concentrations (measured in volume percent).

c. EGME, DiEGME and 23 candidate additives were evaluated. Descriptions and chemical structures of each additive are shown in enclosure (1).

d. This report reviews only the effectiveness of the 25 FSII/potential FSII additives at preventing icing; it does not compare their effectiveness as biocidal agents.

2. Method of Testing FSII Additive Performance.

a. Test Apparatus. The test apparatus used to compare the performance of the FSII additives was the U.S. Navy Fuel System Icing Simulator (FSIS) located at the Naval Air Warfare Center Aircraft Division, Trenton, NJ (NAVAIRWARCENACDIVTRENTON) test facility. This test rig is a small scale, recirculating simulator which can be used to test the effectiveness of FSII additives at varying concentrations and varying amounts of total water. See enclosure (2) for a schematic diagram of the FSIS test rig.

b. Test Protocol.

(1) The test protocol used for developing data on each of the additives tested is outlined in enclosure (3).

(2) For the purposes of comparing the effectiveness of each of the compounds in preventing ice formation, the same additive free jet fuel was used with all FSII additives and candidate additives.

(3) Additive concentration was varied within the range 0.00 to 0.50 volume percent.

3. Discussion. As indicated in references (c) and (d), FSII, because of its hydrophilic nature, has a tendency to become depleted in the fuel bulk transportation/storage system as it comes in contact with water. This means that it is possible to have FSII levels in fuel entering aircraft that is below the minimum concentration required by specifications (see references (a) and (b) for specification concentrations of FSII in military aviation jet fuel). The current Navy

requirement for FSII concentration in fuel being delivered to aircraft (reference (e)) is 0.03 volume percent; current Army/Air Force/NATO requirement for fuel being delivered to aircraft (reference (f)) is 0.07 volume percent. The upper use limit (references (a), (b), (d), (e) and (f) is 0.20 volume percent. These in service limits on FSII concentration in fuel delivered to aircraft provided the target range for additive concentrations tested in the FSIS test rig (0.03 to 0.20 volume percent). In order to establish the bottom end of the additive performance curves, concentrations of 0.00, 0.01 and 0.02 volume percent were also evaluated. In order to provide feedback to developers which might prove useful in the synthesis of additional potential FSII additives, the M- series and CE- series additives were tested at concentrations higher than 0.20 volume percent.

4. Results.

a. Enclosure (4), (Figures 1 through 24) display both the raw data and curves fitted to this data for each of the 13 additives tested during the period June 1993 to February 1997. Each Figure contains three graphs: Additive Concentration vs. Test Time, Additive Concentration vs. Fuel Temperature and Test Time vs. Fuel Temperature.

(1) Additive Concentration vs. Test Time. This graph answers the question, "How long will it take the water in the fuel to freeze and plug up the filter for a given concentration of additive?" and displays the time it takes to reach 35 psi differential pressure across the 30 micron filter for a given additive concentration. The upper time limit for the test is fixed at six hours (360 minutes); if the differential pressure of 35 psi is not encountered prior to this time, the test is shut down. (Extensive testing has shown that if the additive concentration is enough to reach six hours without the differential pressure reaching 35 psi, the test can be run virtually non-stop without the filter differential pressure ever reaching 35 psi).

(2) Additive Concentration vs. Fuel Temperature. This graph answers the question "What is the lowest fuel temperature than can be achieved for a given additive concentration before the water in the fuel freezes and clogs the filter?" and displays the fuel temperature reached at test termination for a given additive concentration. The lowest temperature reached (-37 to -39°C) is set by the NESLAB cooling unit which is part of the FSIS test rig.

(3) Test Time vs. Fuel Temperature. This graph answers the question "Is the FSIS test rig operating properly?" and displays the cool down characteristics of the FSIS test rig from ambient room temperature to the lowest fuel temperature which the NESLAB cooling unit is set to reach. Extensive statistical analysis of numerous tests run with EGME and DiEGME in JP-5 was used to generate a baseline time/temperature repeatability curve against which subsequent operation of the FSIS test rig could be compared to ensure proper performance of the FSIS test rig.

b. Enclosure (5) outlines the types of curve fits used to compare the test results. These curve fit types were used for all additives tested with the exception of M-4, M-6, M-7, M-14, M-15, M-17 through M-21, M-23, M-24, M-26 and CE-1 (candidates with extremely poor performance; data was nearly flat in all cases).

5. Conclusions.

a. Enclosures (6) and (7) are graphical comparisons of the performance of the FSII additives tested. Using the performance of DiEGME (the current military FSII additive) as a baseline, enclosure (6) displays those additives which are considered to be either successful as FSII's or candidates for further research. In like manner, enclosure (7) displays those additives which are considered to be failures as possible FSII's. The following observations concerning the FSII testing can be made.

(1) The FSIS test rig performed properly with all FSII additives as shown in the Test Time vs. Fuel Temperature graphs (enclosure (4)).

(2) M-1 is not a viable FSII additive at the concentrations currently accepted as normal (maximum 0.20 volume percent DiEGME). In order to provide any anti-icing protection, a high concentration (>0.29 volume percent) is required. M-1 exhibits almost an on/off behavior in the first of the three graphs, Figure 5 of enclosure (4), (Additive Concentration vs. Test Time) and nearly linear behavior in the second of the three graphs (Additive Concentration vs. Fuel Temperature).

(3) EGME (no longer used as a military FSII additive) is marginally less effective than DiEGME as an FSII additive (slightly to the right of DiEGME in the additive Concentration vs. Test Time graph, Figure 1 of enclosure (4), and slightly above DiEGME in the Additive Concentration vs. Fuel Temperature graph).

(4) M-2 is slightly less effective than DiEGME as an FSII additive (a little to the right of DiEGME in the Additive Concentration vs. Time graph (Figure 6 of enclosure (4)) and a little above DiEGME in the Additive Concentration vs. Fuel Temperature graph). Recent work, reference (g), indicates possible environmental problems with the use of this compound as a fuel additive due to the formaldehyde used in its synthesis.

(5) C-1 (the commercial equivalent of M-2) displays performance nearly identical to DiEGME. The minor differences in performance between C-1 and M-2 are most likely due to the differences in impurities between the two compounds (M-2 is a purer compound than C-1). Like M-2, there are possible environmental problems with the use of this compound as a fuel additive due to the formaldehyde which is used in its synthesis (reference (g)).

(6) DPM and DPG are a little bit more effective than DiEGME as FSII additives (slightly to the left of DiEGME in the Additive Concentration vs. Test Time graph (Figures 3 and 4 of enclosure (4)) and slightly below DiEGME in the Additive Concentration vs. Fuel Temperature graph).

(7) M-3 performed less effectively than DiEGME. On the Additive Concentration vs. Test Time graph (Figure 7 of enclosure (4)) it displays a gently increasing performance instead of the sharply rising increase indicative of DiEGME, EGME, M-2, M-22 and C-1. On the Additive Concentration vs. Fuel Temperature graph (Figure 7 of enclosure (4)) it's response is flatter than, and above that of DiEGME. Environmental concerns with other additive candidates indicate that this compound should continue to be studied.

(8) M-16 is not a viable FSII additive at the concentrations currently accepted as normal (maximum 0.20 volume percent DiEGME). In order to provide any anti-icing protection, a high concentration (>0.30 volume percent) is required.

(9) M-22 performed slightly better than DiEGME at concentrations between 0.01 and 0.06 volume percent (above DiEGME in the Additive Concentration vs. Test Time graph (Figure 19 of enclosure (4)) and below DiEGME in the Additive Concentration vs. Fuel Temperature graph). Performance at concentrations between 0.07 and 0.09 volume percent was slightly less than DiEGME on the Additive Concentration vs. Test Time Graph. Performance at concentrations greater than 0.09 volume percent was equal to DiEGME.

(10) M-4, M-6, M-7, M-11, M-14, M-15, M-17, M-18, M-19, M-20, M-21, M-23, M-24, M-26 and CE-1 are considered absolute failures as possible FSII additives. Fuel containing M-4, M-6, M-7 and CE-1 at all concentrations up to 0.50 volume percent behaved in the FSIS rig exactly like fuel containing 0.00 volume percent FSII: complete stoppage of the 30-micron filter occurred between 50 and 60 minutes into the test. The same performance was shown by M-14, M-15, M-17, M-18, M-19, M-20, M-21, M-23, M-24 and M-26. These compounds, however, were only tested at concentrations up to 0.30 volume percent (testing at higher concentrations was not considered necessary based on experience gained during testing of the first several FSII candidates).

(11) M-11, a thick substance (similar to molasses except for color), was not tested in the FSIS rig because when mixed with fuel it settled out and solidified.

(12) M-5, a white powder, has not been tested as of this report. M-8, M-9, M-10, M-12, M-13 and M-25 have not been submitted for testing.

6. <u>Recommendations</u>.

a. <u>General</u>. Performance in the FSIS test rig is only one part of establishing a candidate compound's suitability as an FSII additive (poor performance on the FSIS test rig is grounds for

not considering a candidate compound for further testing but good performance is not necessarily sufficient grounds for continuing testing). Other items which need to be considered are:

(1) Performance in large scale test rigs, such as the U.S. Navy Low Temperature Fuel Flow Simulator (LTFFS).

(2) Environmental Compatibility

(a) How easy will it be to dispose of fuel storage tank water bottoms which contain FSII?

(b) Is the candidate compound on any regulatory listings of hazardous, or potentially hazardous substances?

(3) Interaction with other current and proposed jet fuel additives and the effect of candidate FSII additives on other jet fuel specifications (such as flash point and thermal stability).

(4) Effectiveness as a biocidal agent (assuming that what is desired is one additive which will perform as both an FSII and a biocide similar to DiEGME).

(5) Cost of production (and in the case of developmental additives, the time needed to establish cost effective production.

b. Specific.

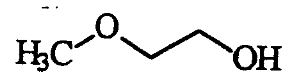
(1) Additional testing in the U.S. Navy LTFFS rig are indicated for the following FSII candidates: DPG, M-2/C-1, M-3 and M-22. A decision on environmental and toxicological testing should be delayed until the results of LTFFS testing are available.

(2) Additional testing is not warranted for DPM (same family of glycol ethers as EGME and DiEGME which may prove to be environmentally troublesome or otherwise restricted by regulations), M-1, M-16 (performance not close enough to DiEGME), M-4, M-6, M-7, M-11, M-14, M-15, M-17, M-18, M-19, M-20, M-21, M-23, M-24, M-26 and CE-l.

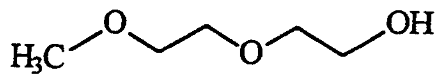
(3) Continue to test additional compounds from George Mason University and other developers as they become available.

DESCRIPTIONS OF FSII'S EVALUATED

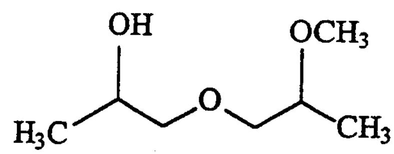
(1) Ethylene Glycol Monomethyl Ether (EGME): FSII additive used in JP-4 fuel from the 1960's thru 1993, in JP-8 fuel thru 1993, and, in JP-5 fuel from the 1960's thru late 1970's. Empirical formula: $C_3H_8O_2$.



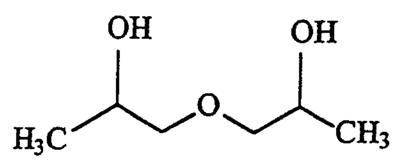
(2) Di-Ethylene Glycol Monomethyl Ether (DiEGME): Standard military FSII additive used since the late-1970's in JP-5 and in JP-8 since 1993. Empirical formula: $C_5H_{12}O_3$.



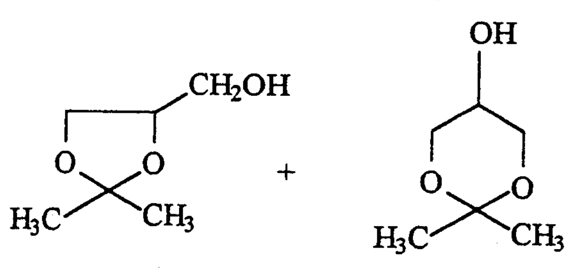
(3) Di-Propylene Glycol Methyl Ether (DPM): A commercial compound looked at as a possible FSII additive. Empirical formula: $C_7H_{16}O_3$.



(4) Di-Propylene Glycol (DPG): A commercial compound looked at as a possible FSII additive. Empirical formula: $C_6H_{14}O_3$.

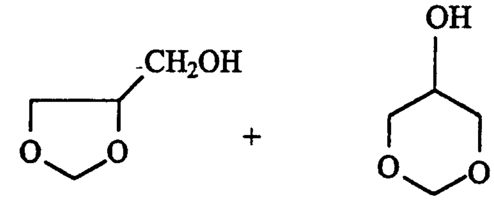


(5) 2,2-Dimethyl-1,3-Dioxolane-4 Methanol (M-1): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_6H_{12}O_3$.



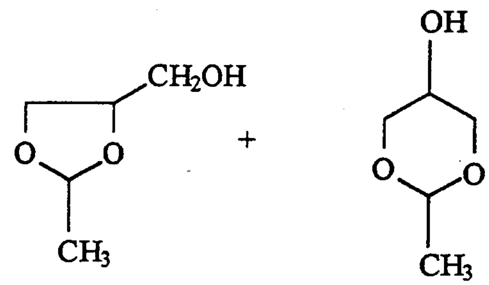
(Mixture of α and β forms)

(6) 1,3-Dioxolane-4-Methanol (M-2): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_4H_8O_3$.



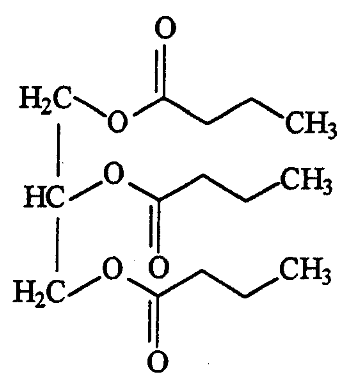
(Mixture of α and β forms)

(7) 2-Methyl-1,3-Dioxolane-4-Methanol (M-3): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_5H_9O_3$.

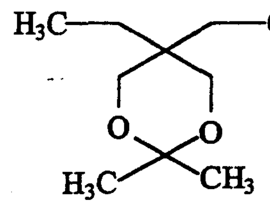


(Mixture of α and β forms)

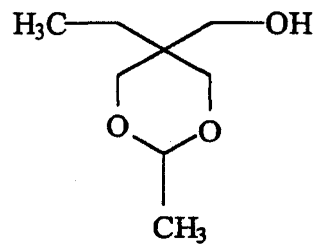
(8) Tri n-Butyl Ester of Glycerol (M-4): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_{15}H_{26}O_6$.



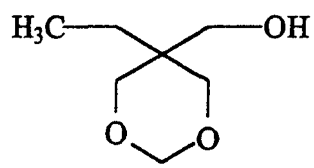
(9) Acetone Adduct of Trimethylol Propane (M-6): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_9H_{18}O_3$.



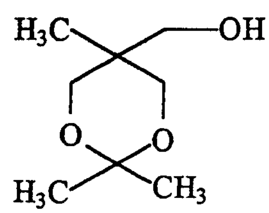
(10) Acetaldehyde Adduct of Trimethylol Propane (M-7): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_8H_{16}O_3$.



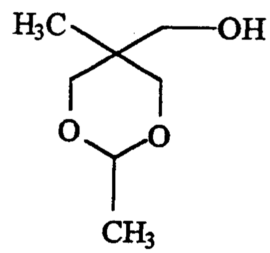
(11) Formaldehyde Adduct of Trimethylol Propane (M-11): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_7H_{14}O_3$.



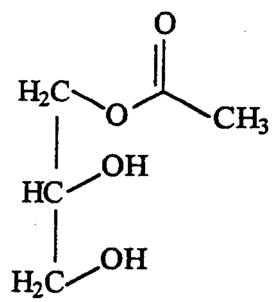
(12) 1,1,1-Tris(hydroxymethyl)Ethane Acetone Adduct (M-14): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_8H_{16}O_3$.



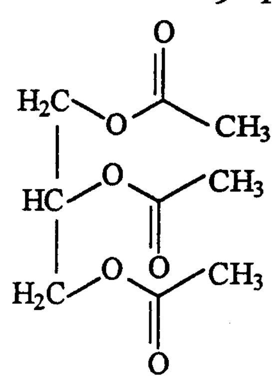
(13) 1,1,1-Tris(hydroxymethyl)Ethane Acetaldehyde Adduct (M-15): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_7H_{14}O_3$.



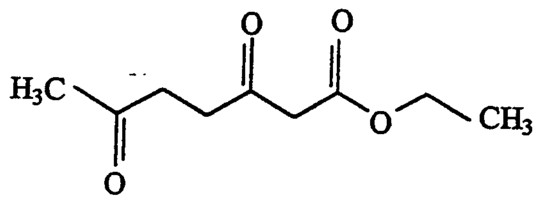
(14) Monoacetate Ester of Glycerol (M-16): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_5H_{10}O_4$.



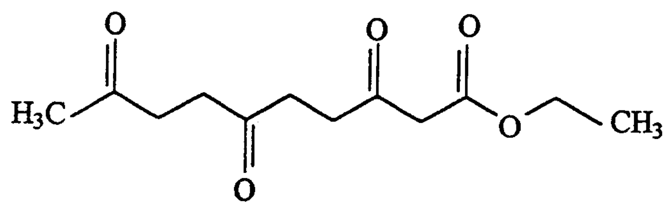
(15) Triacetate Ester of Glycerol (M-17): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_9H_{14}O_6$.



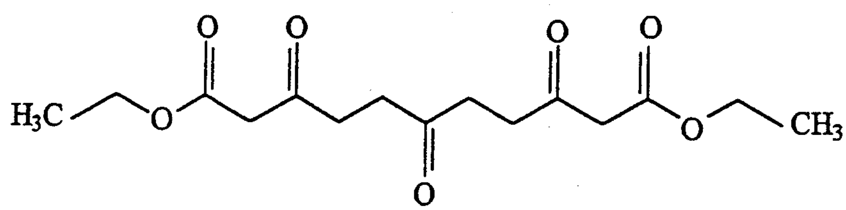
(16) Ethyl 3,6 Dioxaheptanoate (M-18): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_9H_{14}O_4$.



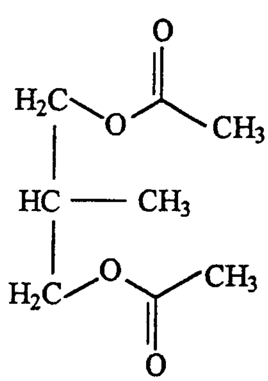
(17) Ethyl 3,6,9 Trioxadecanoate (M-19): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_{12}H_{14}O_5$.



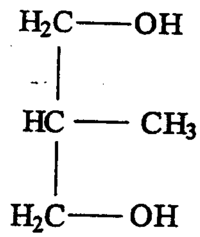
(18) Diethyl 3,6,9 Trioxaundecandioate (M-20): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_{15}H_{22}O_7$.



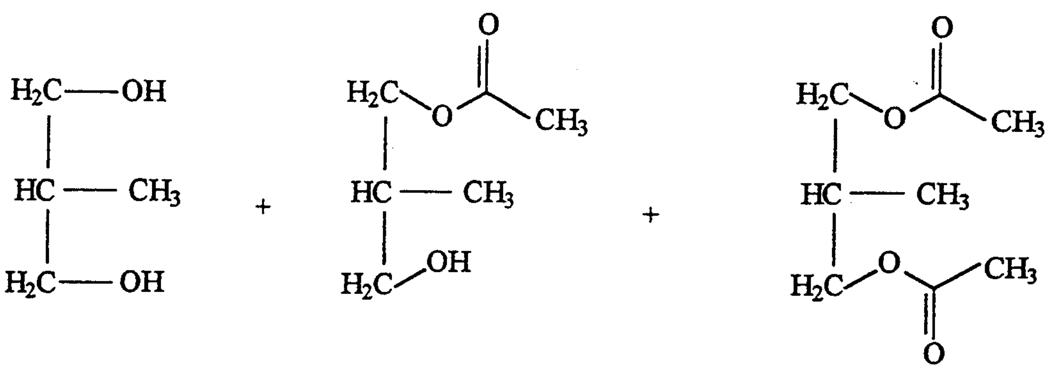
(19) 2-Methylpropane-1,3-Diacetate (M-21): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_8H_{14}O_4$.



(20) 2-Methyl-1,3-Propanediol (M-22): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_4H_{10}O_2$.

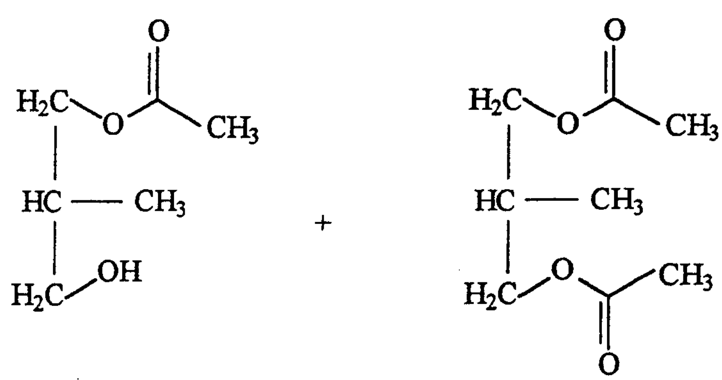


(21) A mixture of three components (8% 2-Methyl-1,3-Propanediol; 48% 3-Hydroxy-2-MethylPropyl Acetate; 44% 2-Methylpropane-1,3-Diacetate) (M-23): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate.



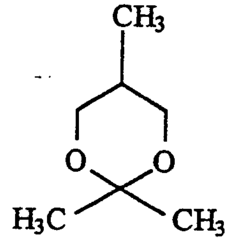
2-Methyl-1,3-Propanediol 3-Hydroxy-2-MethylPropyl Acetate 2-Methylpropane-1,3-Diacetate

(22) A mixture of two components (45% 3-Hydroxy-2-MethylPropyl Acetate; 55% 2-Methylpropane-1,3-Diacetate) (M-24): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate.

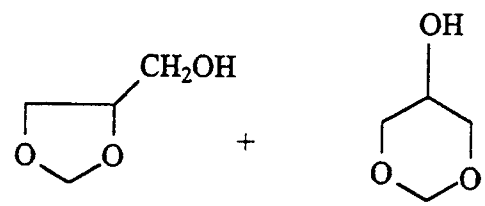


3-Hydroxy-2-MethylPropyl Acetate 2-Methylpropane-1,3-Diacetate

(23) Acetone Adduct of M-22 (M-26): A compound synthesized at George Mason University as part of the joint U.S. Navy/U.S. Air Force FSII development project; an environmentally friendly FSII candidate. Empirical formula: $C_7H_{14}O_2$.



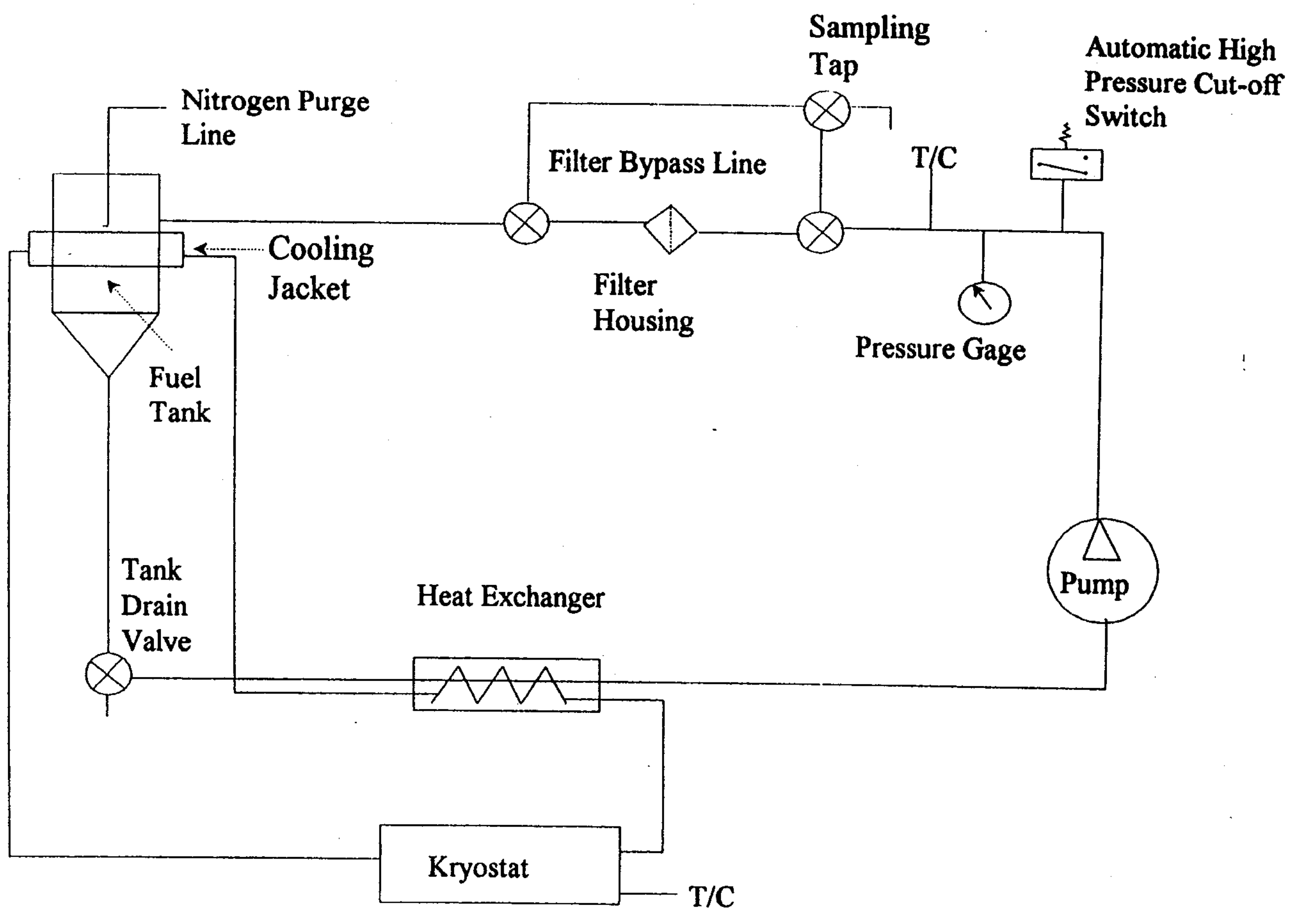
(24) Glycerol Formal (C-1): A commercially available form of M-2. Empirical fomula: $C_4H_8O_3$.



(Mixture of α and β forms)

(25) Aspen Systems Additive (CE-1): A Crown Ether derivative provided by Aspen Systems. This additive was provided as 3.5 grams of a solid dissolved in 100 milliliters of Jet A. Empirical formula and structure not provided.

Schematic of FSIS Test Rig



Description of FSIS Test Protocol

Test Fluid	Additive free JP-5/JP-8 plus FSII (3500 ml)
Fuel Flow	40 ml/s
Fuel Filter	30 micron absolute, wire mesh
Total Water	235 - 265 ppm

1. FSIS test rig is cooled down to -37 to -40 °C while test fluid is being circulated.

2. Circulation is maintained until one of two end conditions is met:

   a. FSIS test rig automatically shuts down when pressure differential across the filter reaches 35 psi.

   b. FSIS test rig is manually shut down when six (6) hours of continuous circulation is reached without the automatic shutdown feature being activated.

FIGURE 1:

EGME Performance Graphs (Data taken 28 Jun 93 to 8 Nov 93)

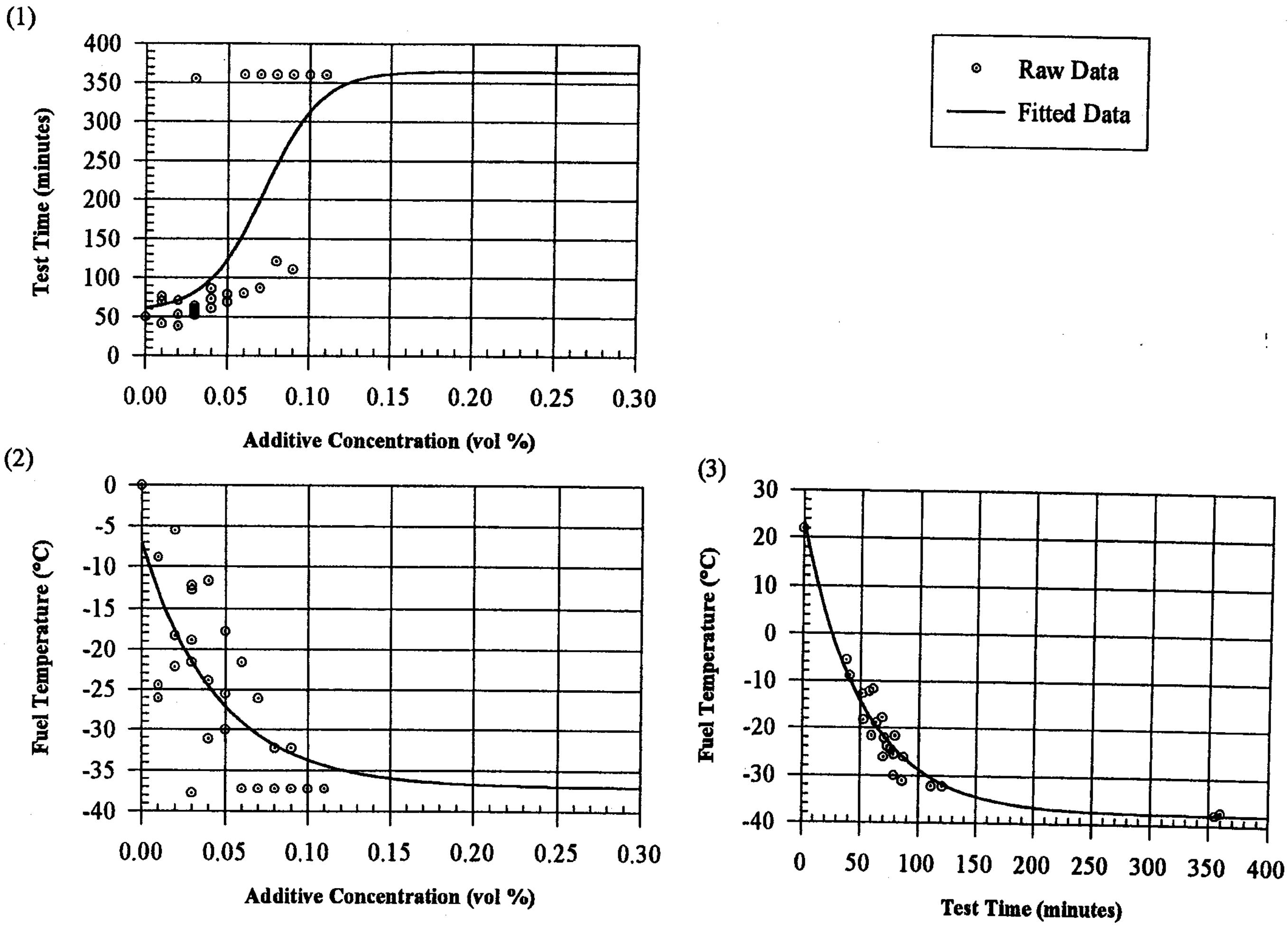


FIGURE 2:

DiEGME Performance Graphs (Data taken 21 Jun 93 to 21 Jul 94; 27 Mar 95 to 9 May 96)

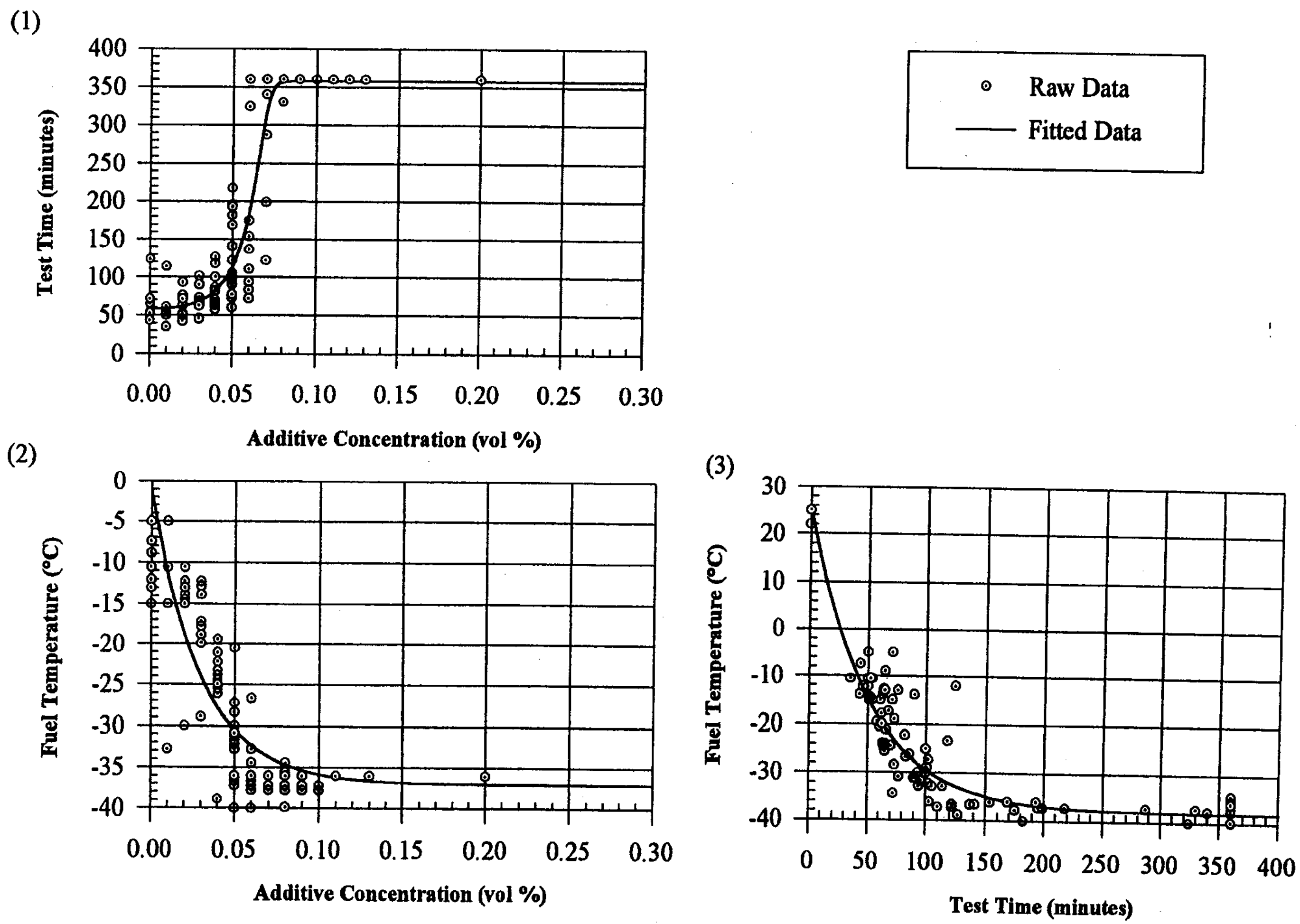


FIGURE 3:

DPM Performance Graphs (Data taken 22 Dec 93 to 29 Mar 94)

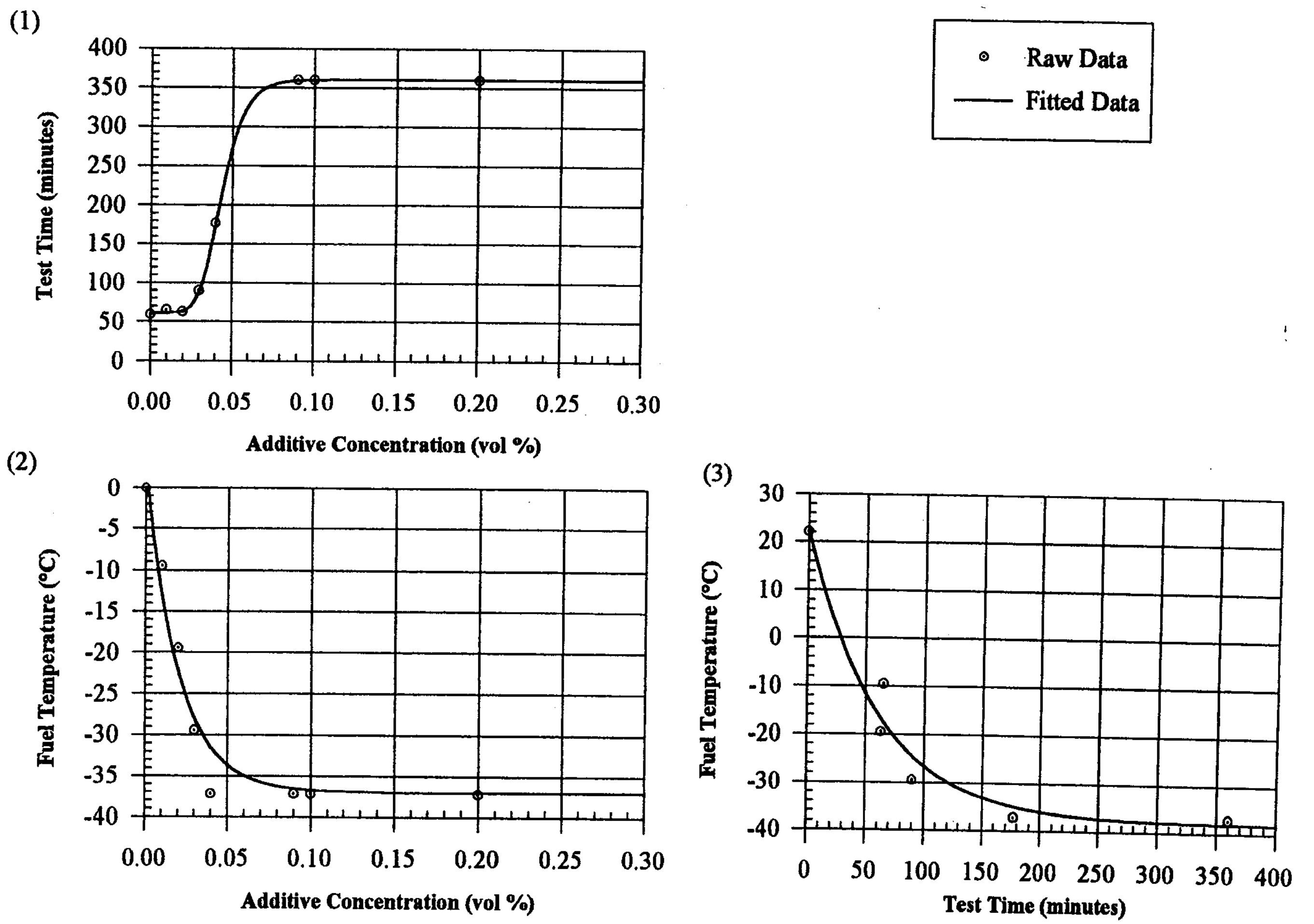


FIGURE 4:

DPG Performance Graphs (Data taken 30 Mar 94 to 12 Dec 94)

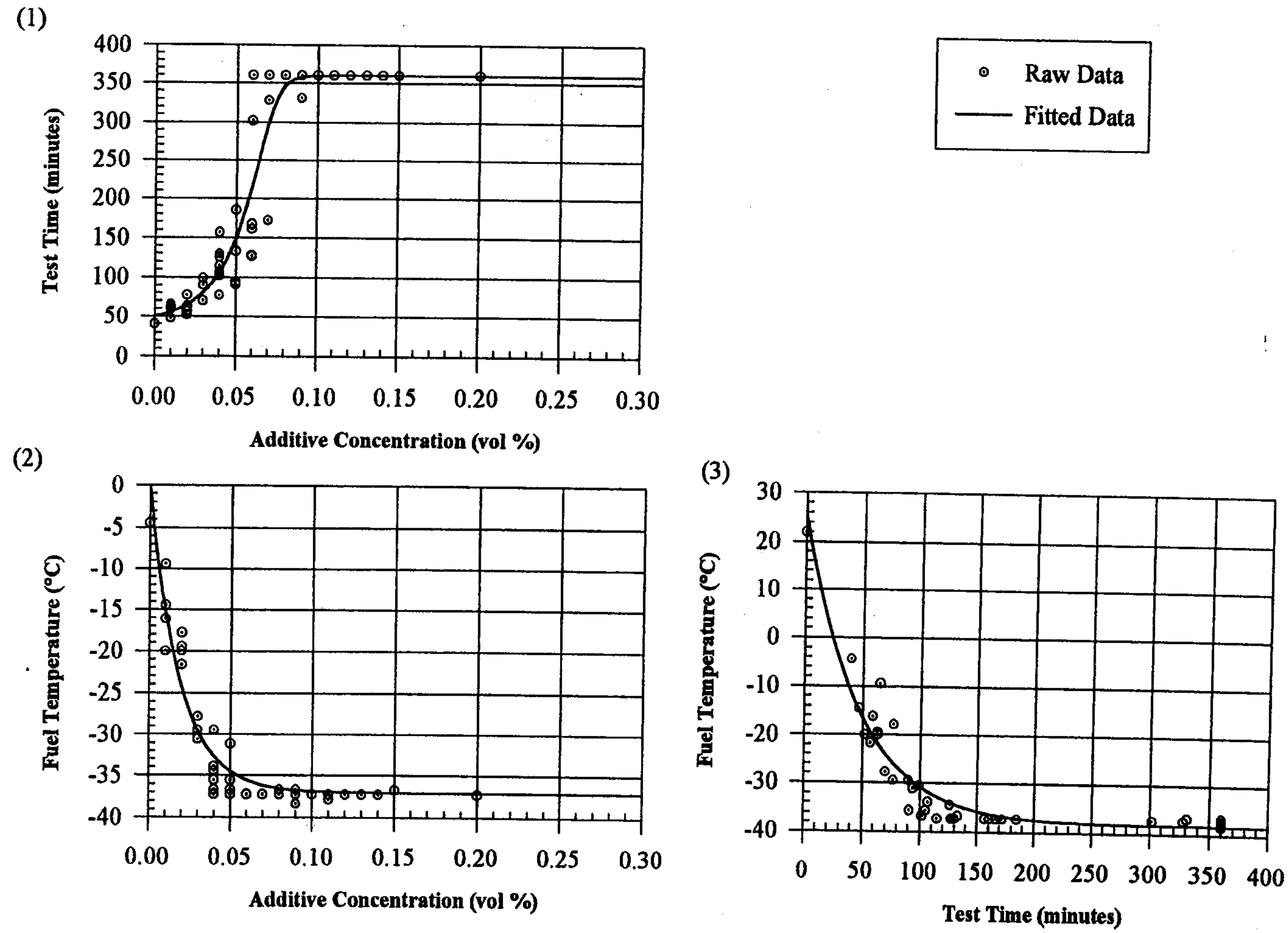


FIGURE 5:

M-1 Performance Graphs (Data taken 26 Oct 94 to 30 Nov 94)

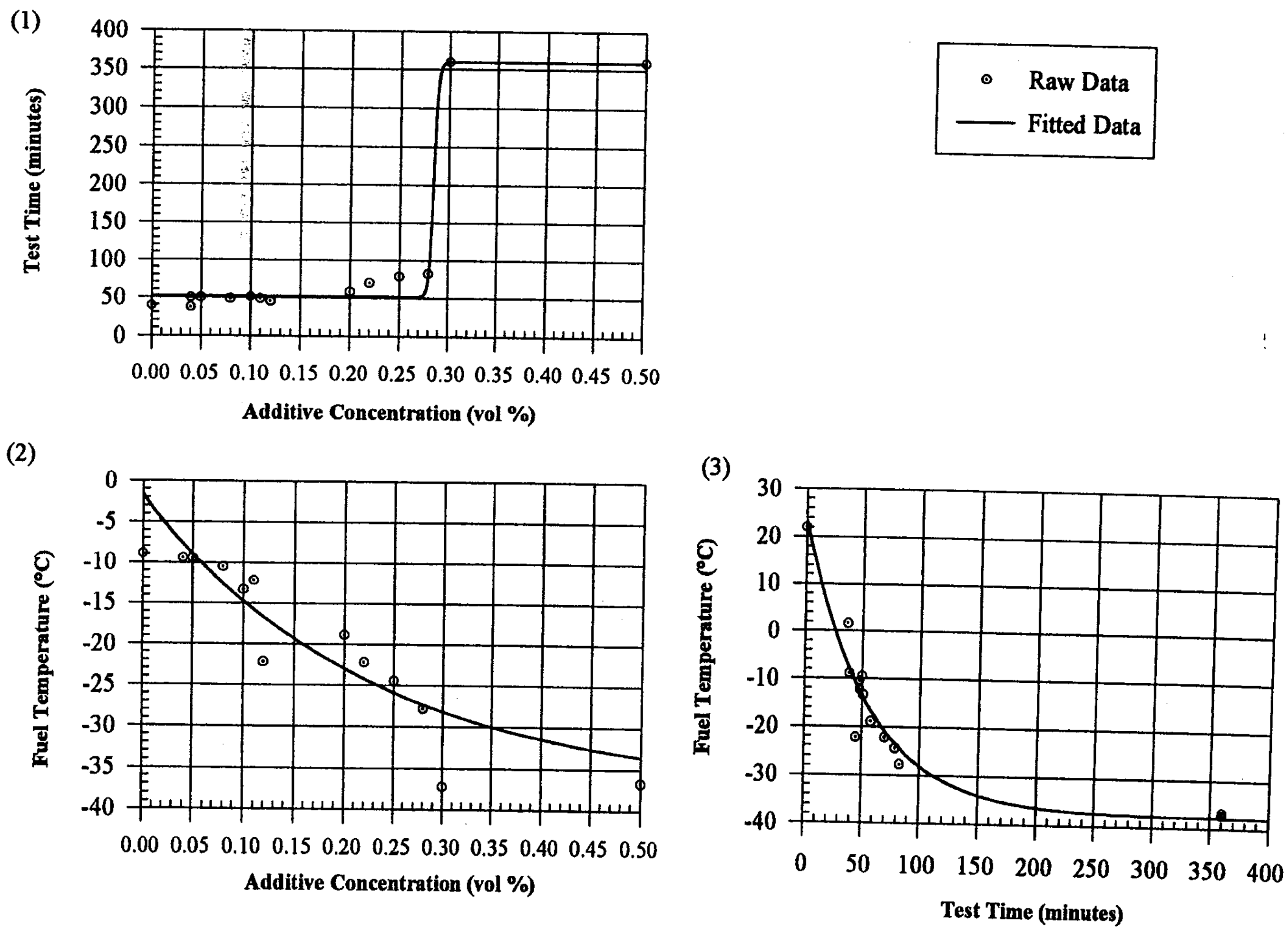


FIGURE 6:

M-2 Performance Graphs (Data taken 12 Dec 94 to 22 Jun 95)

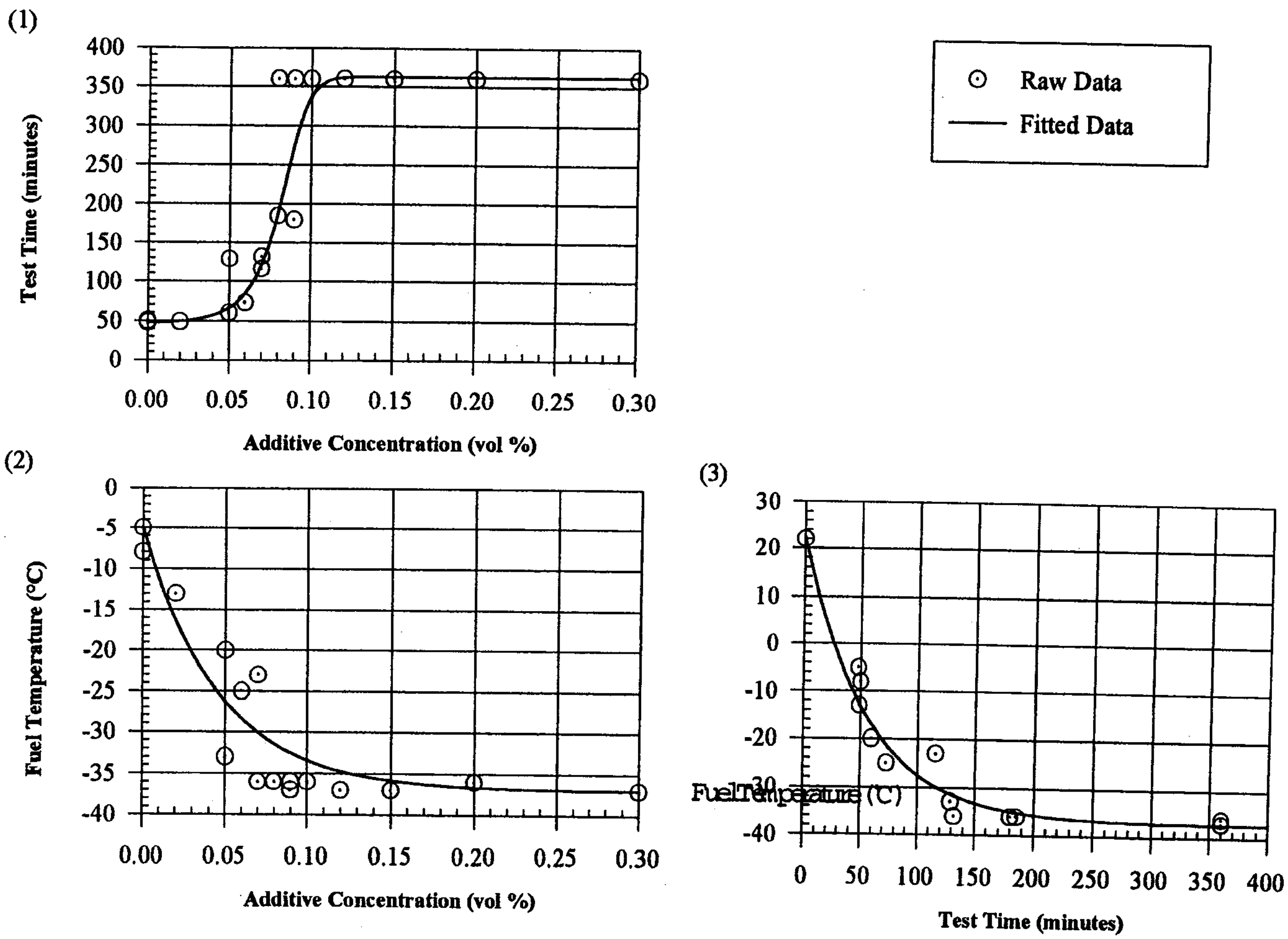


FIGURE 7:

M-3 Performance Graphs (Data taken 9 Aug 95 to 27 Sep 95)

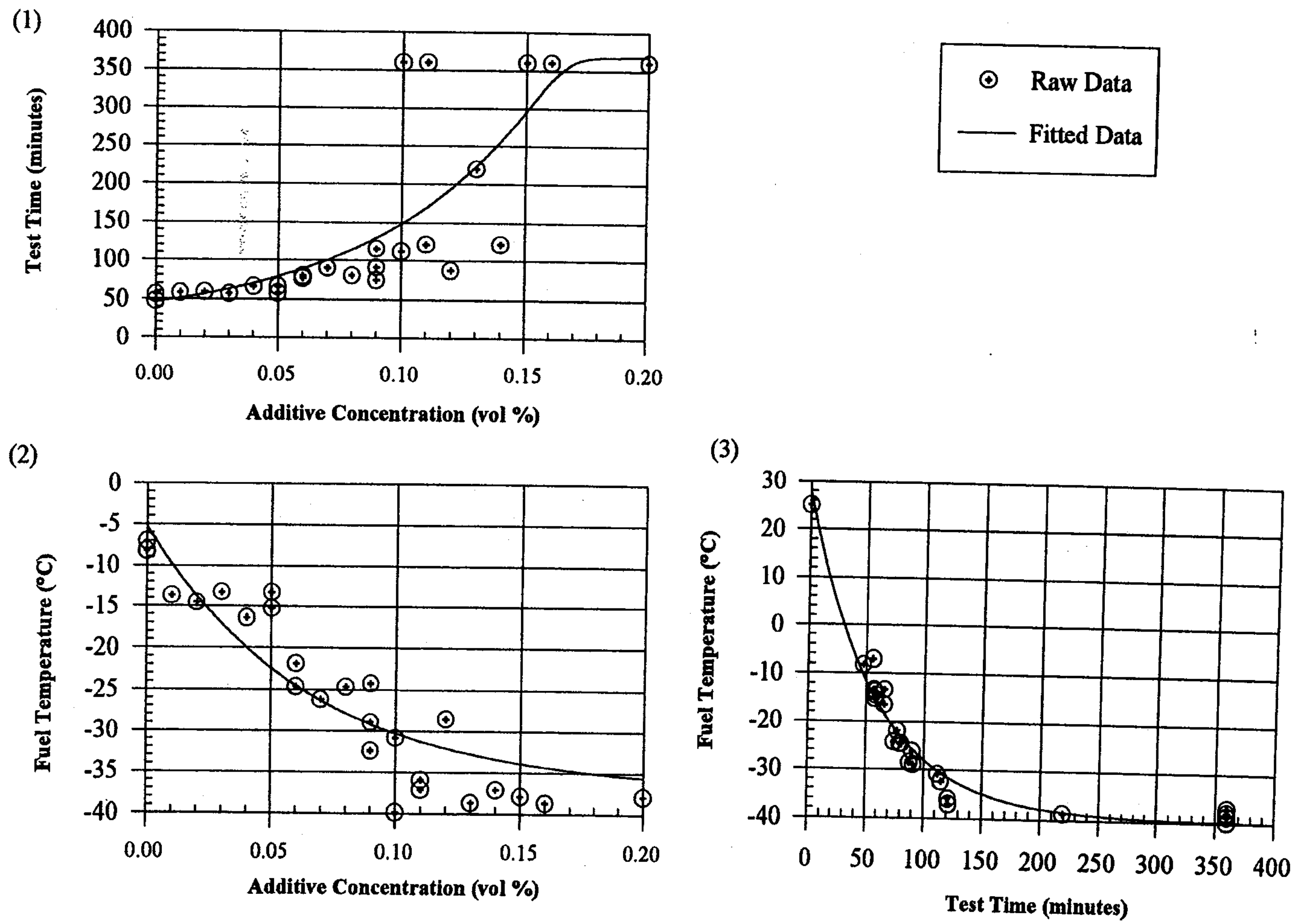


FIGURE 8:

M-4 Performance Graphs (Data taken 31 May to 8 Jun 95)

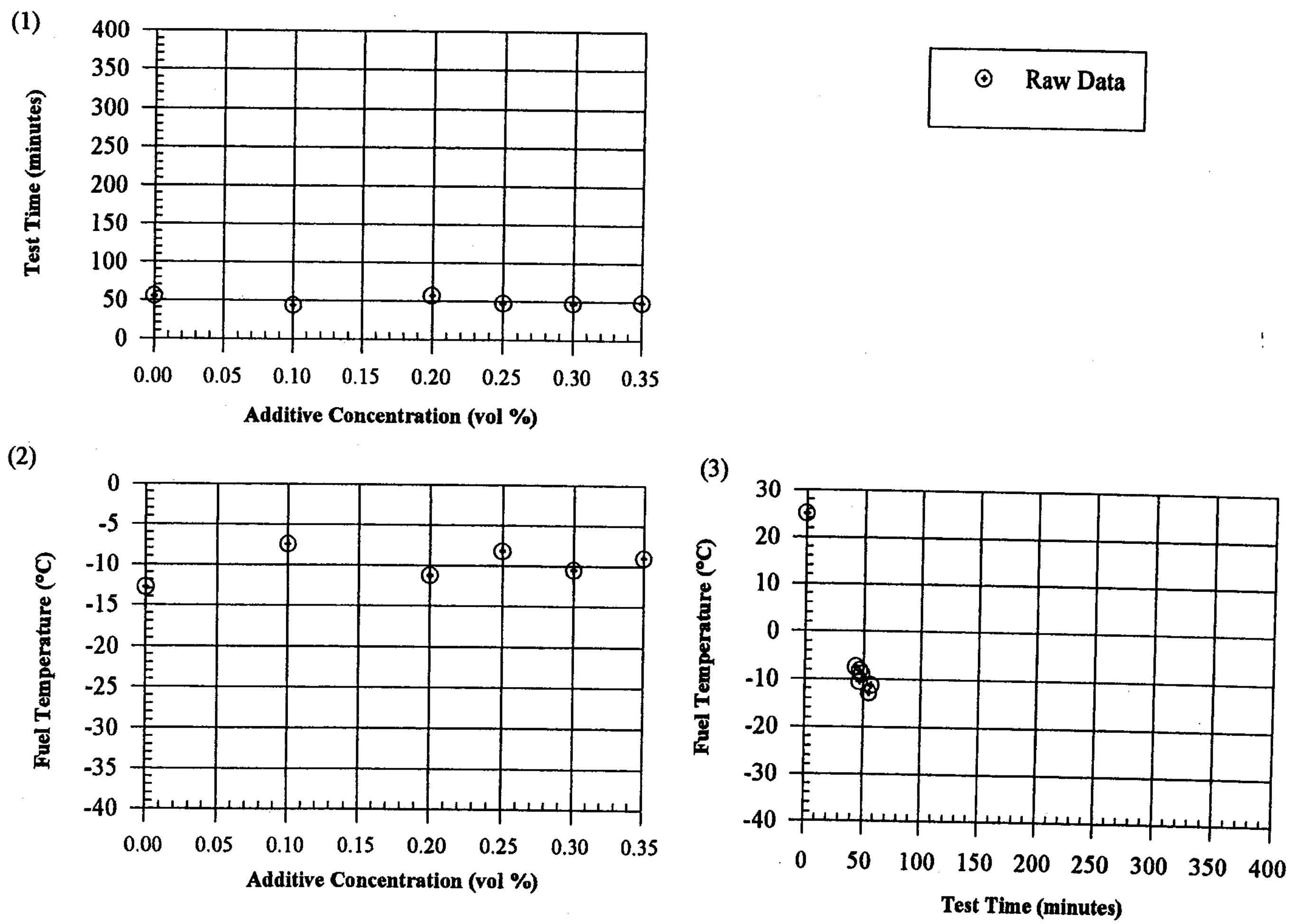


FIGURE 9:

M-6 Performance Graphs (Data taken 23 Jan 96 to 14 Feb 96)

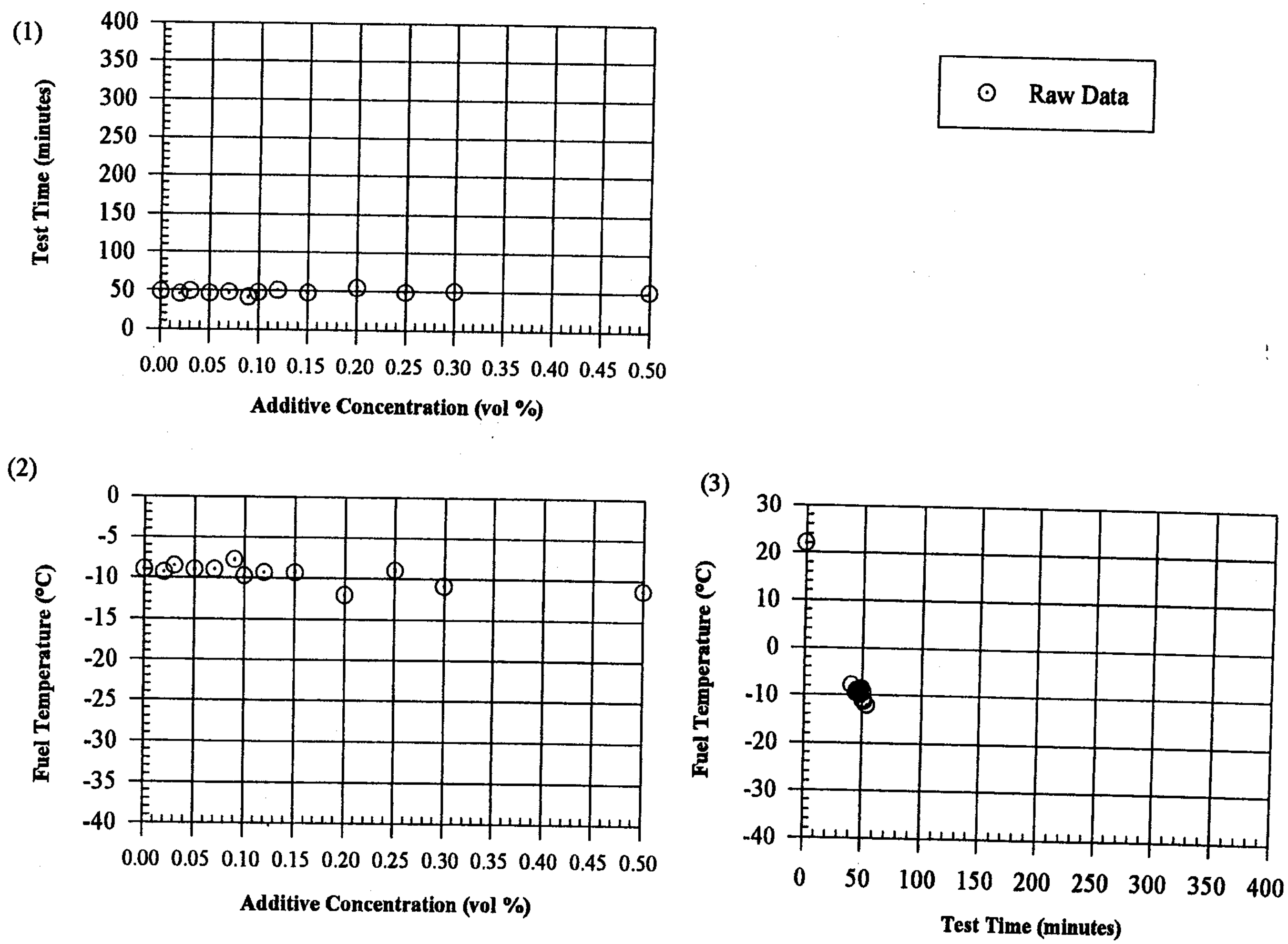


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FIGURE 10:

M-7 Performance Graphs (Data taken 13 - 23 May 96)

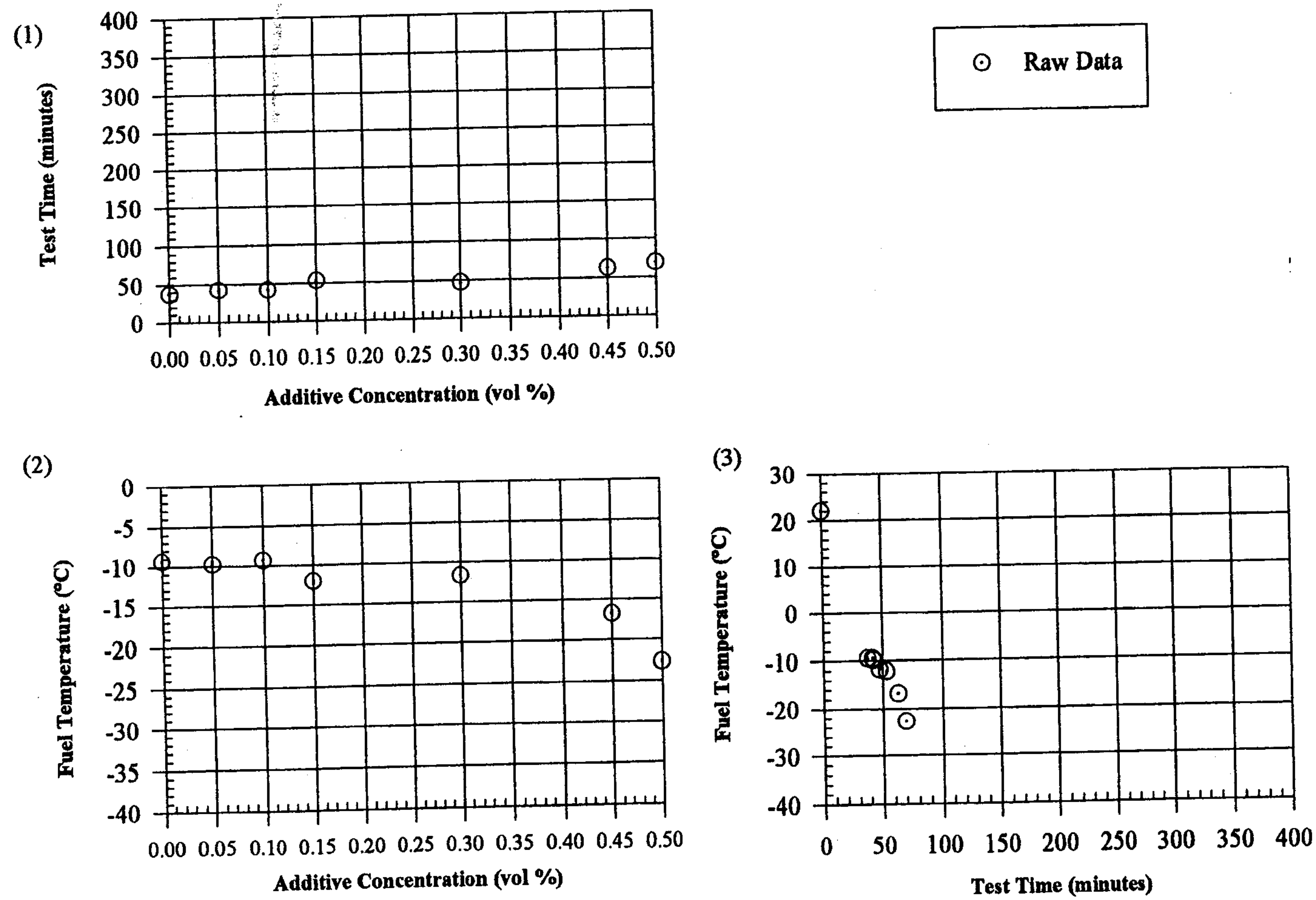


FIGURE 12:

M-15 Performance Graphs (Data taken 26 - 28 Aug 96)

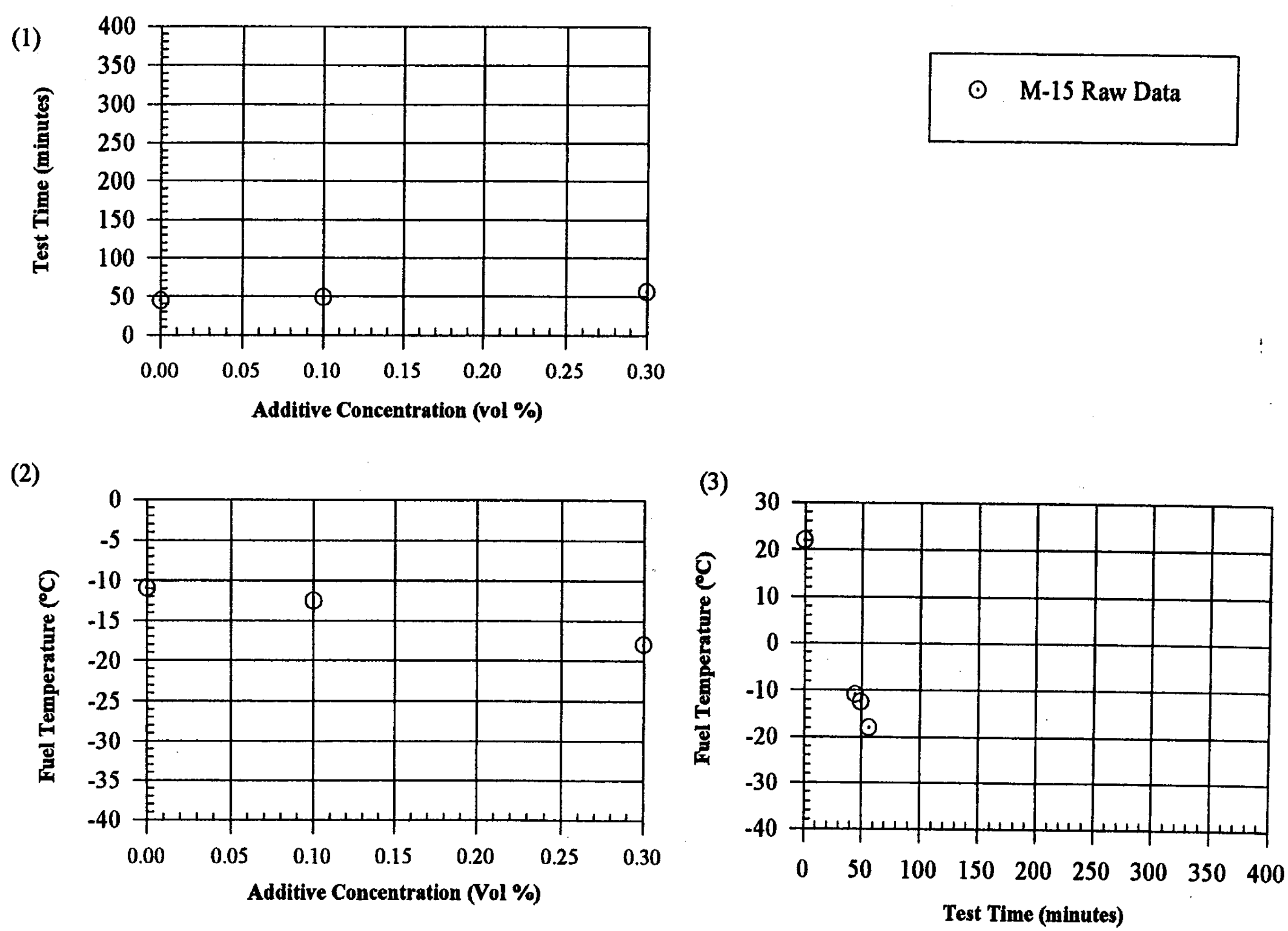


FIGURE 13:

M-16 Performance Graphs (Data taken 9 - 26 Sep 96)

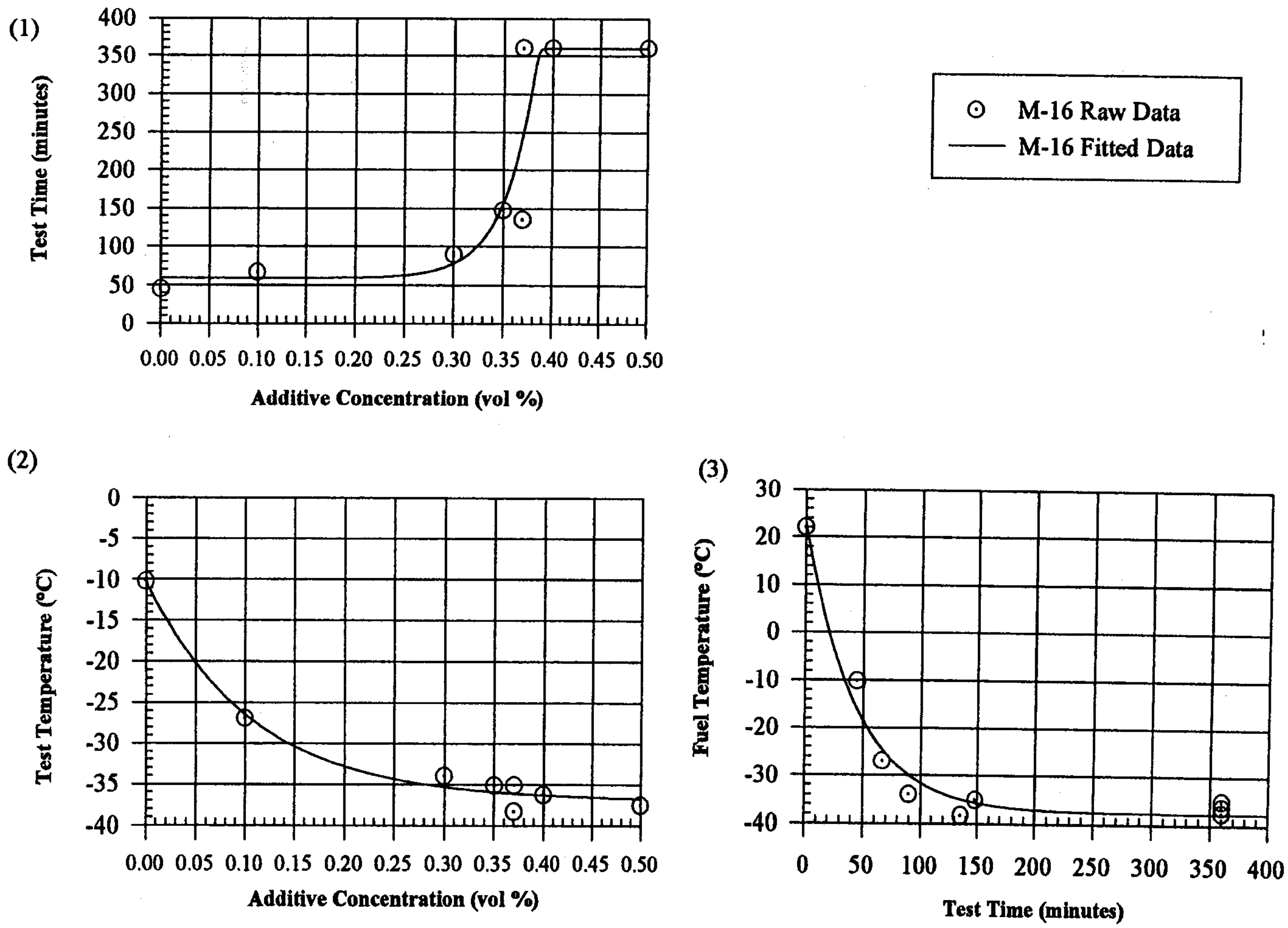


FIGURE 14:

M-17 Performance Graphs (Data taken 11 - 12 Sep 96)

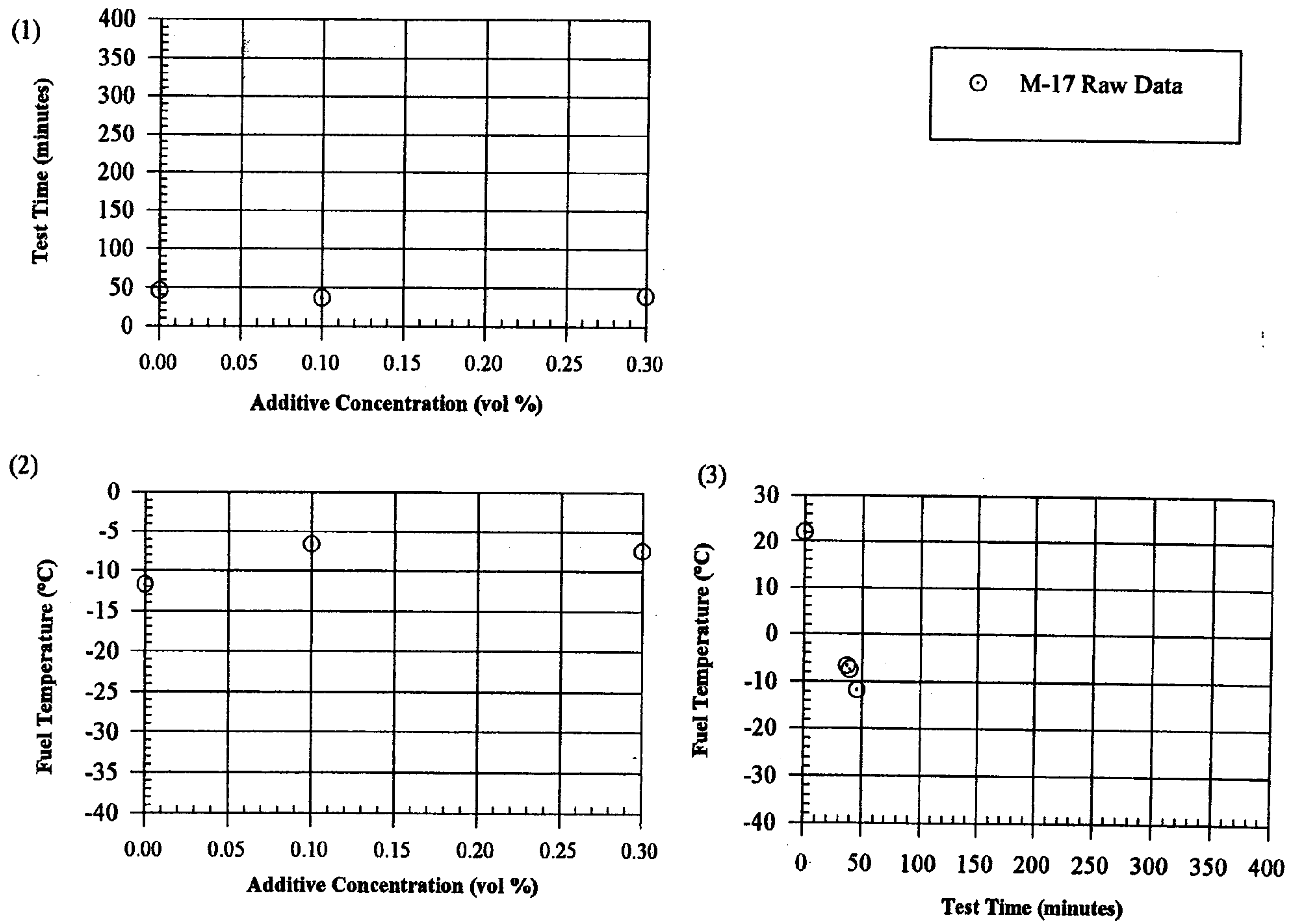


FIGURE 15:

M-18 Performance Graphs (Data taken 1 - 3 Oct 96)

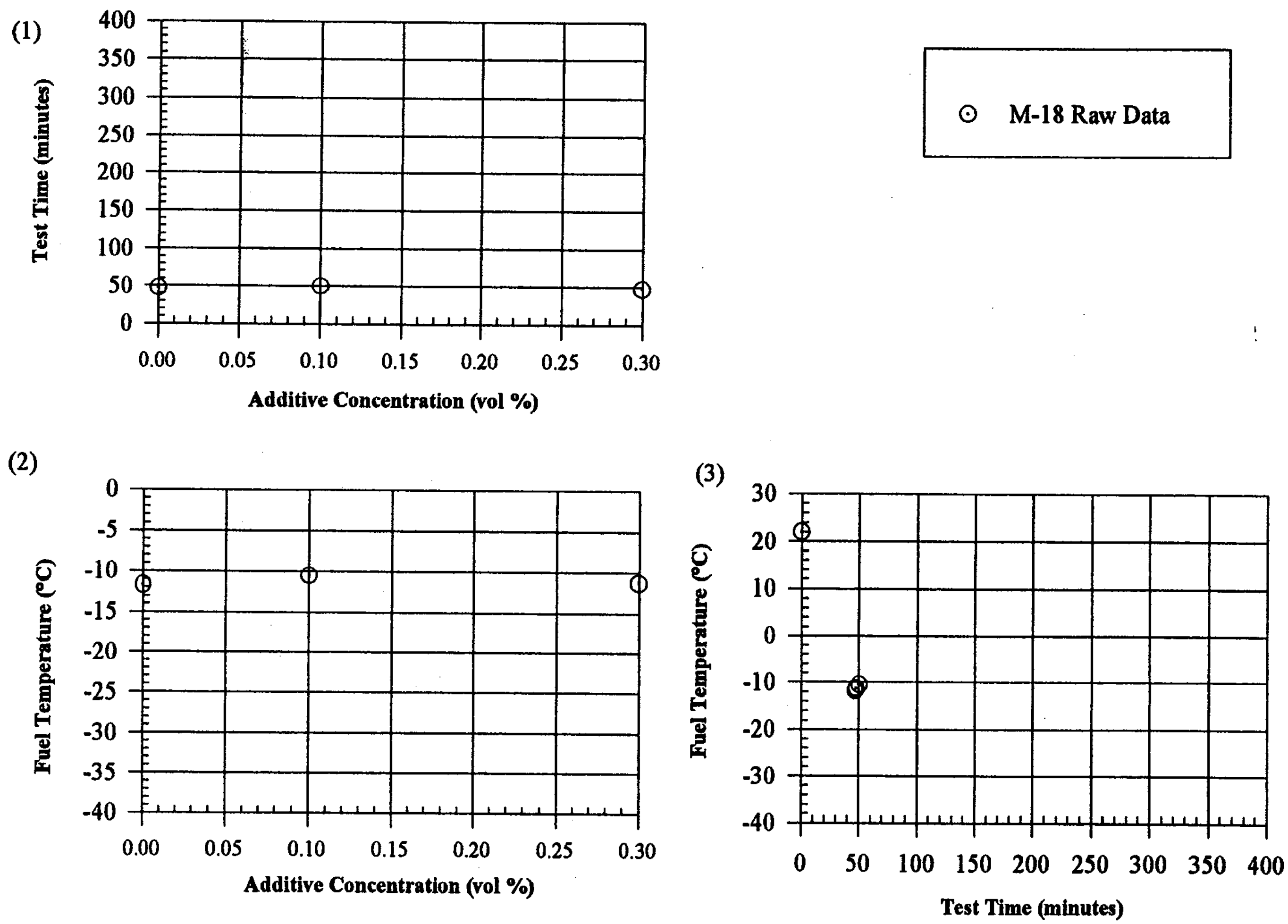


FIGURE 16:

M-19 Performance Graphs (Data taken 8 - 10 Oct 96)

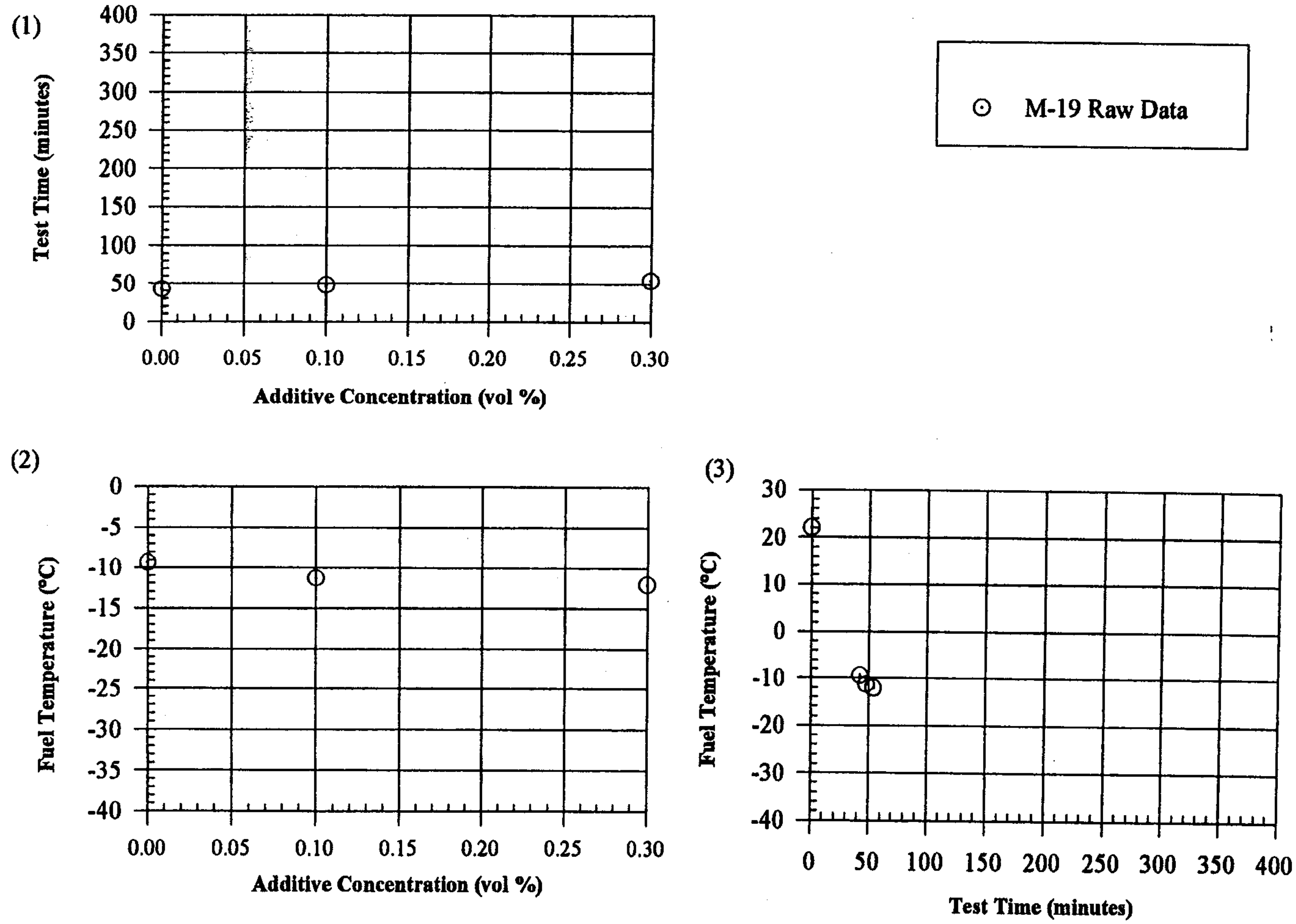


FIGURE 17:

M-20 Performance Graphs (Data taken 16 - 21 Oct 96)

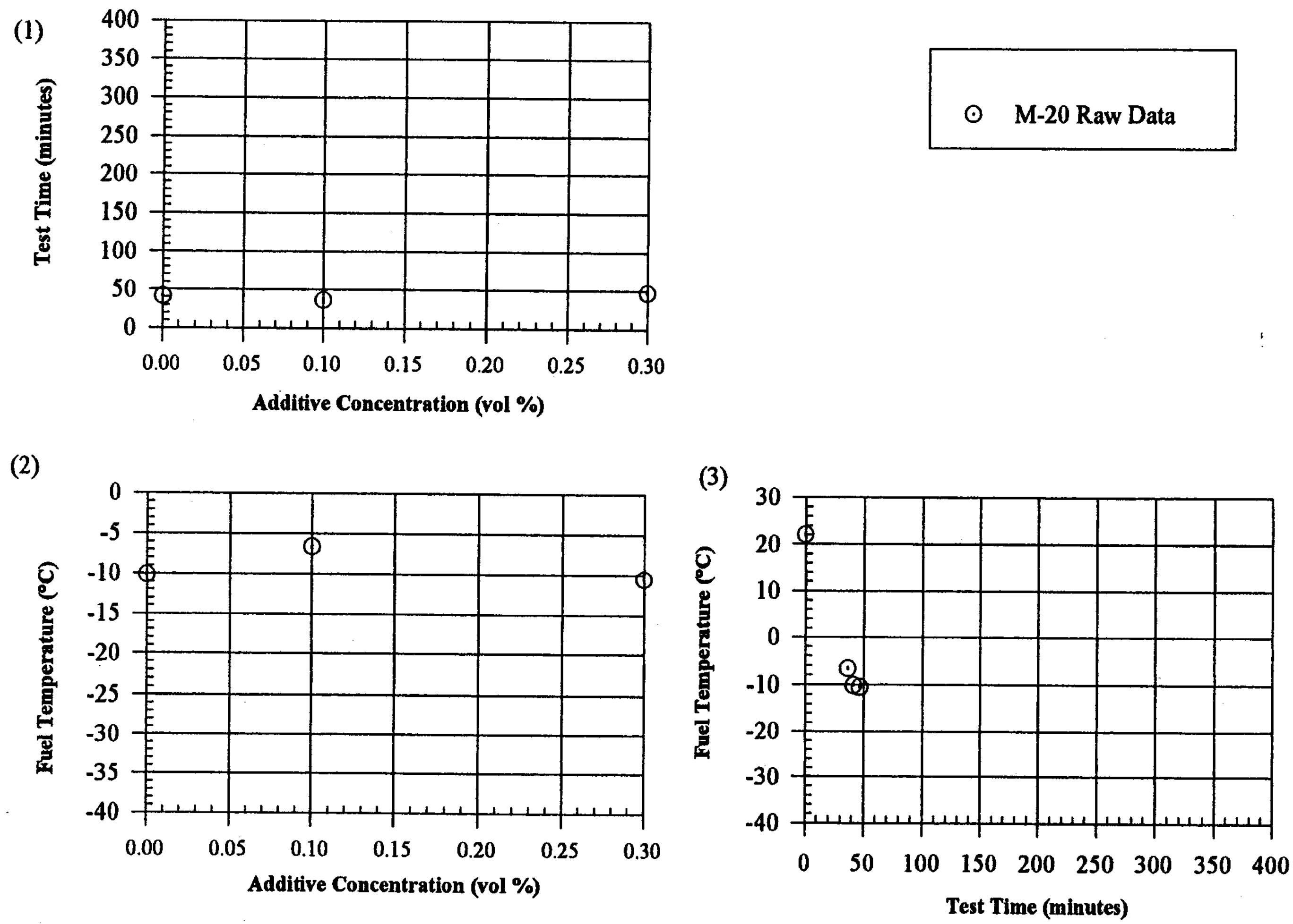


FIGURE 18:

M-21 Performance Graphs (Data taken 29 - 31Oct 96)

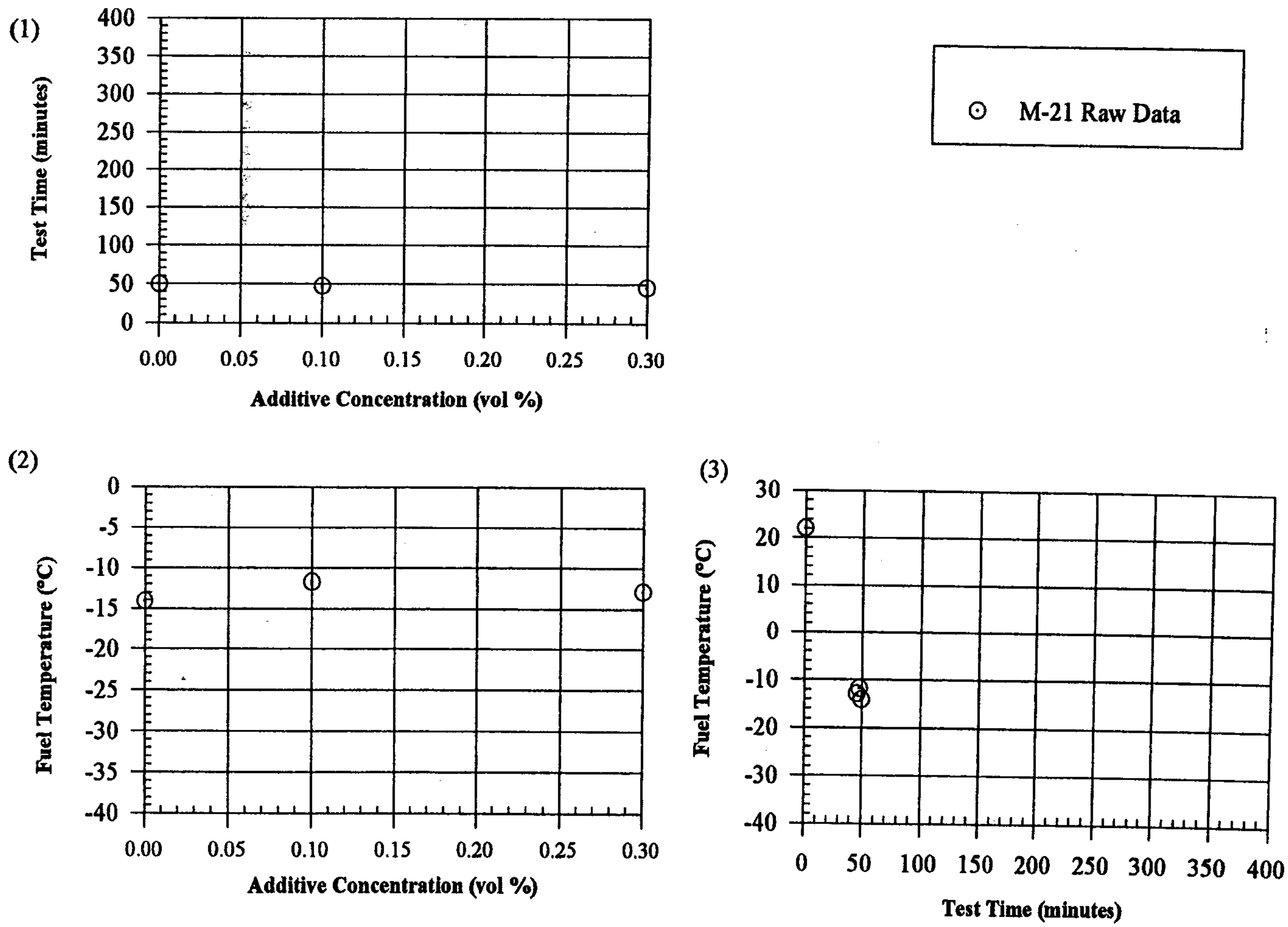


FIGURE 19:

M-22 Performance Graphs (Data taken 31 Oct 96 - 23 Jan 97)

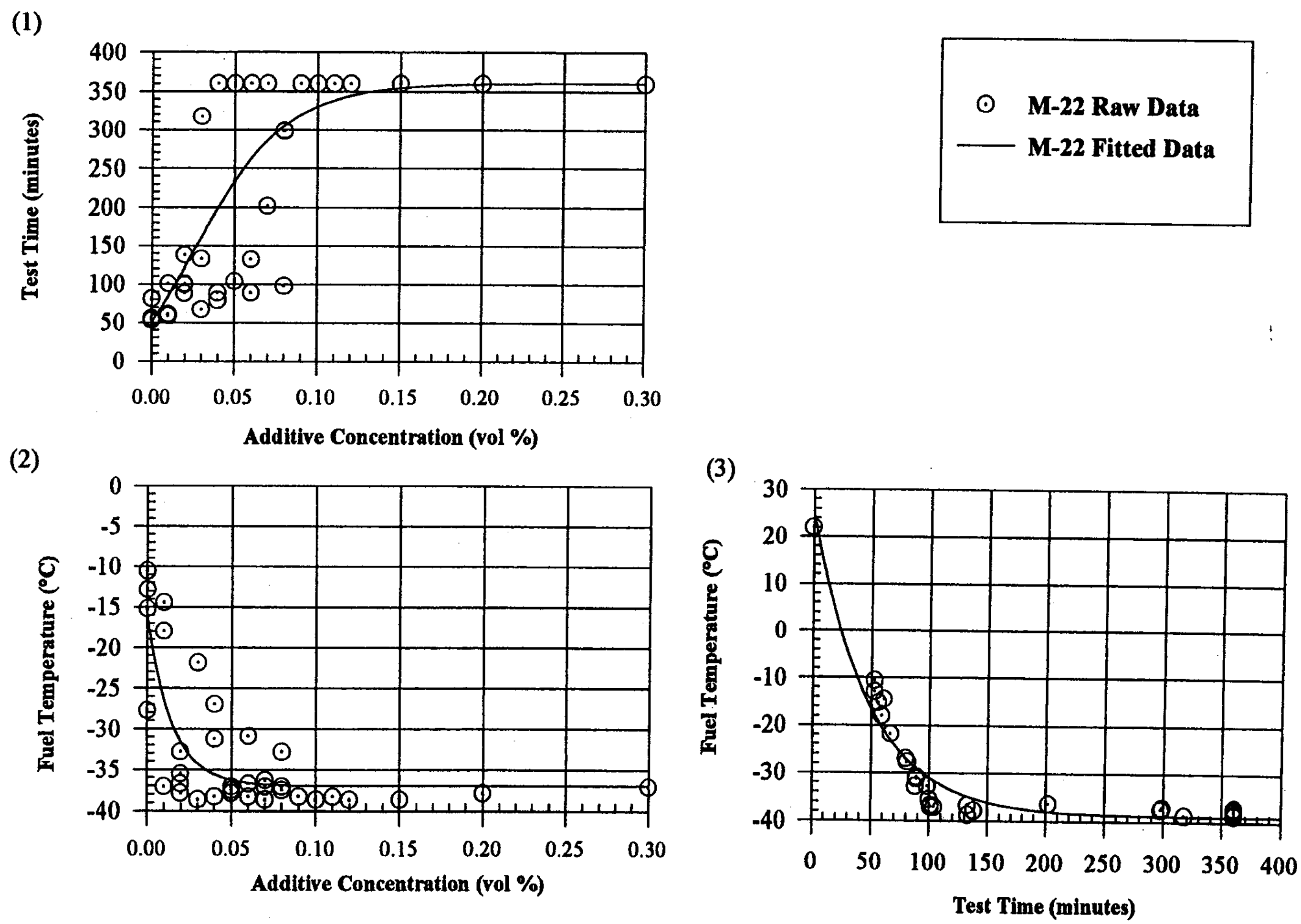


FIGURE 20:

M-23 Performance Graphs (Data taken 7 Nov 96)

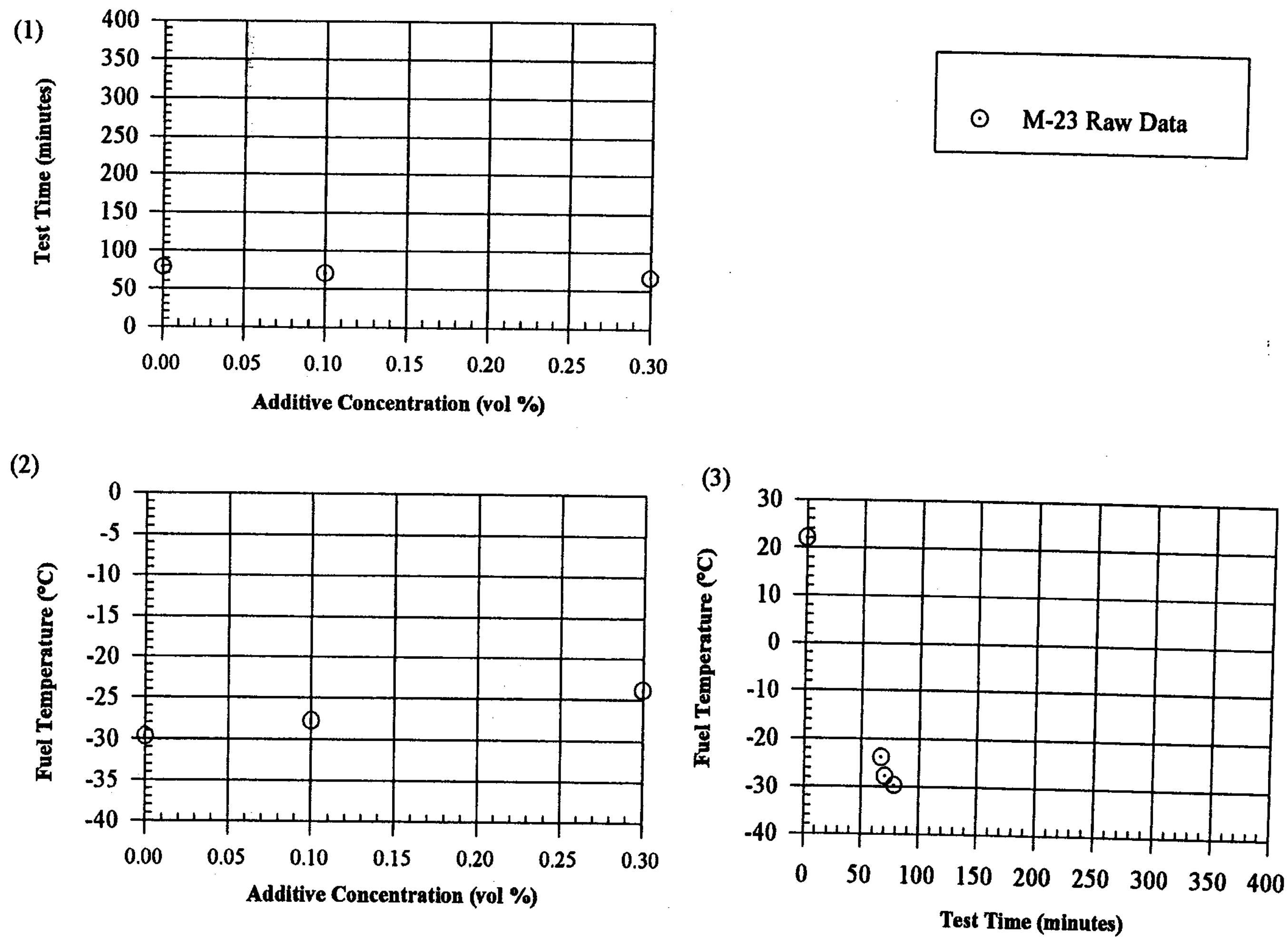


FIGURE 21:

M-24 Performance Graphs (Data taken 8 - 12 Nov 96)

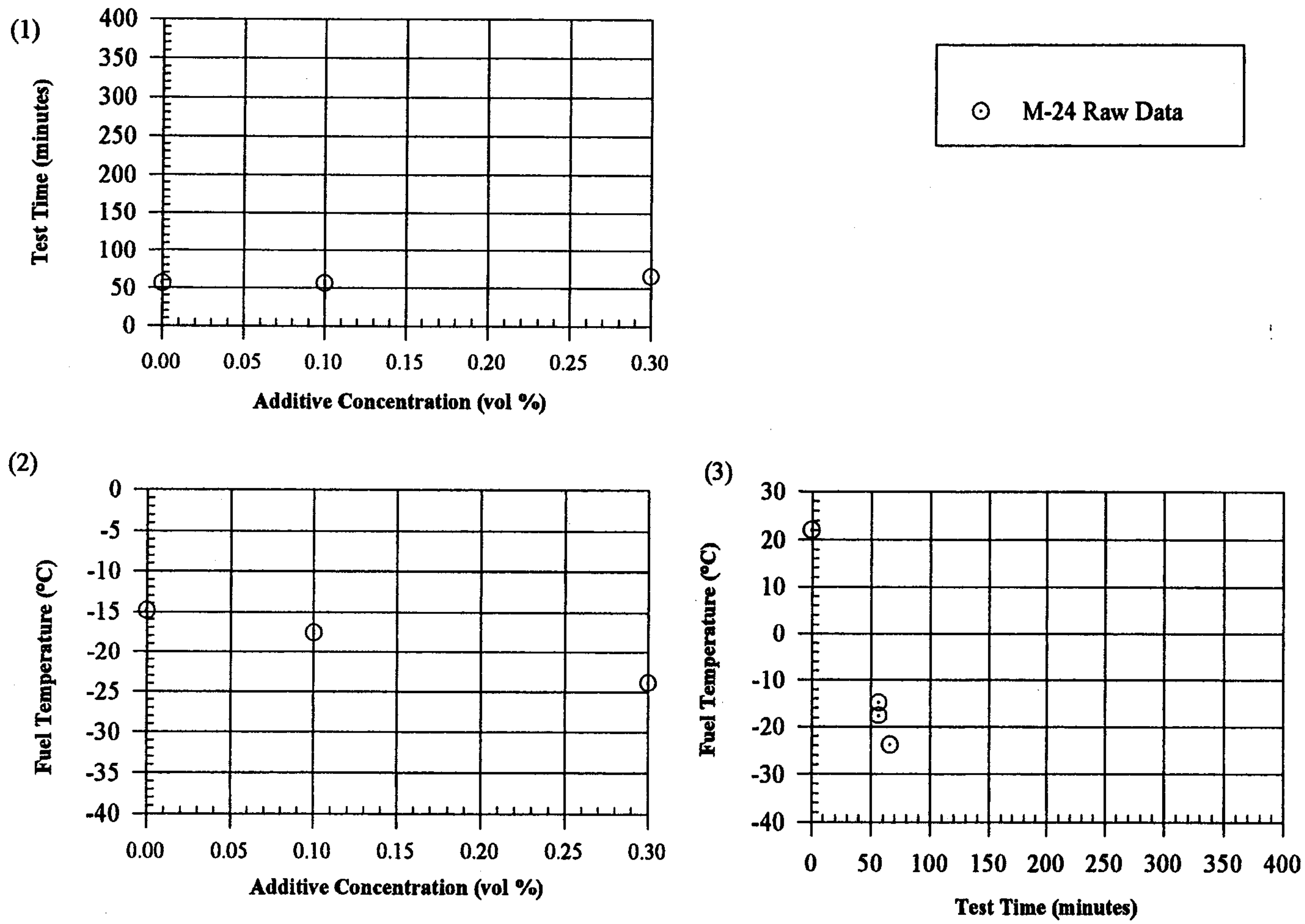


FIGURE 22:

M-26 Performance Graphs (Data taken 6 - 8 Jan 97)

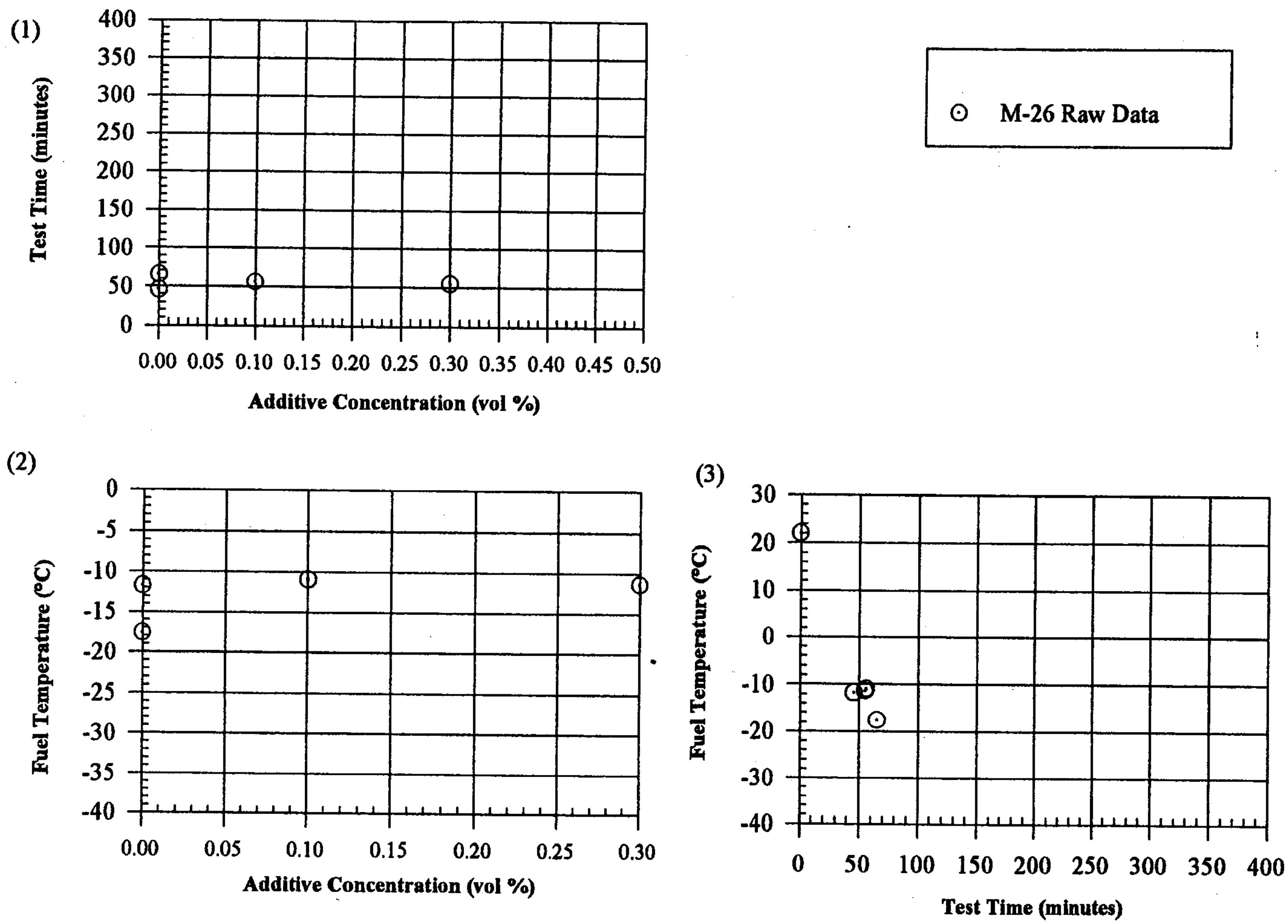


FIGURE 23:

C-1 Performance Graphs (Data taken 28 Sep 95 to 19 Oct 95)

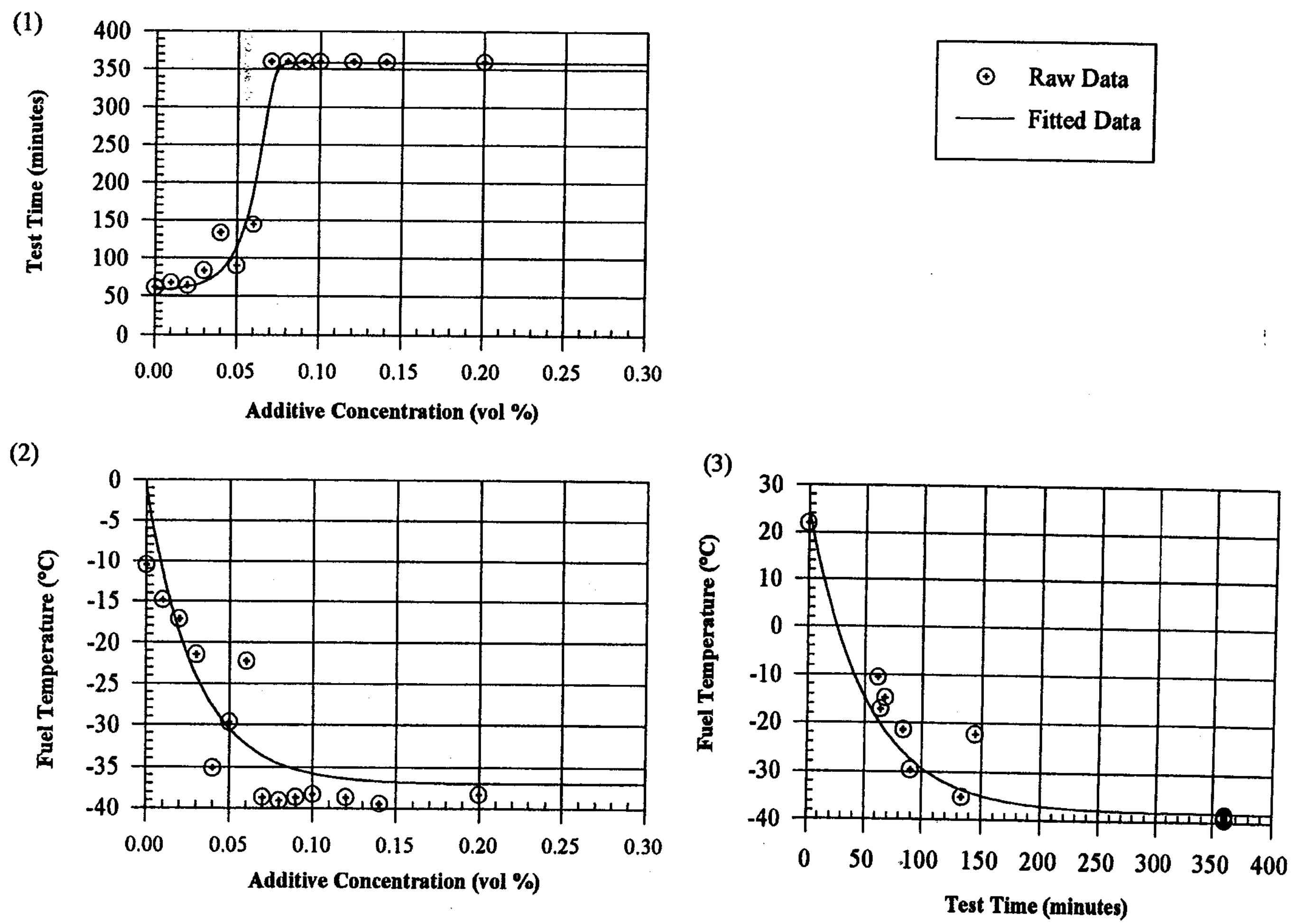
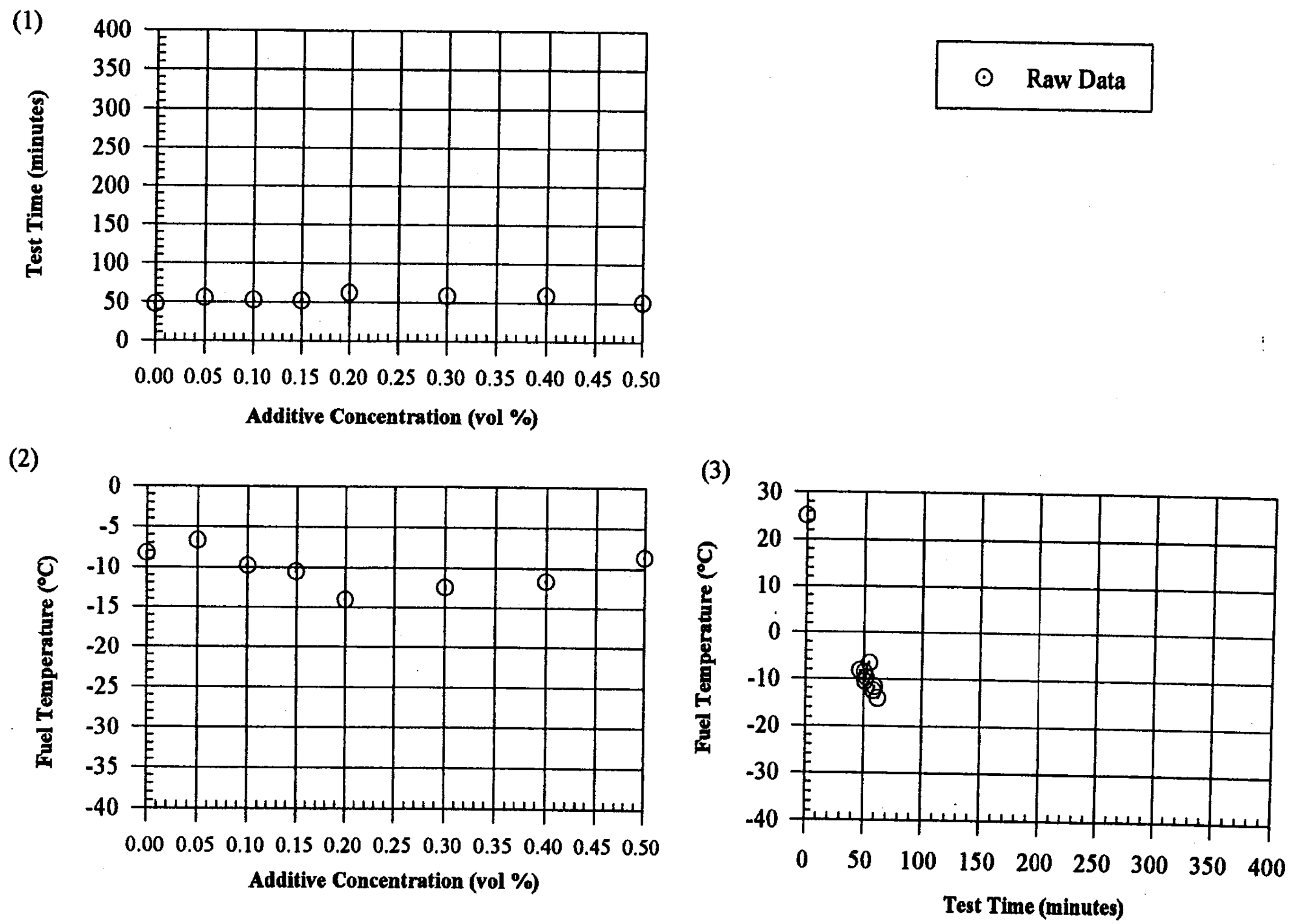


FIGURE 24:

CE-1 Performance Graphs (Data taken 23 Oct 95 to 2 Nov 95)



CURVE FITS USED TO GRAPHICALLY COMPARE DATA SETS

Curve fits were used as a means to graphically compare the performance of different FSII additive and potential additive data sets. The curves fit to the various graphs are as follows:

1. Additive Concentration vs. Test Time: a logistic function (sigmoid) of the form

$$\text{Test Time} = a + [\, b/(\, 1 + e^{\,c(\text{Additive Concentration} - d)})^{f}\,]$$

where

a = time to freeze at 0.00 volume percent
b = range for test time (a + b = curve fit upper limit for test time [arbitrarily set at 360 minutes])
c = slope coefficient (- sign indicates rising slope)
d = volume percent at curve's inflection point
f = symmetry parameter

2. Additive Concentration vs. Fuel Temperature: an exponential decay of the form

$$\text{Fuel Temperature} = a + be^{-c(\text{Additive Concentration})}$$

where

a = lowest temperature experienced (temperature is set so it goes no lower than -37 °C to -40 °C)
b = amplitude of curve (a + b = fuel temperature intercept)
c = rate constant

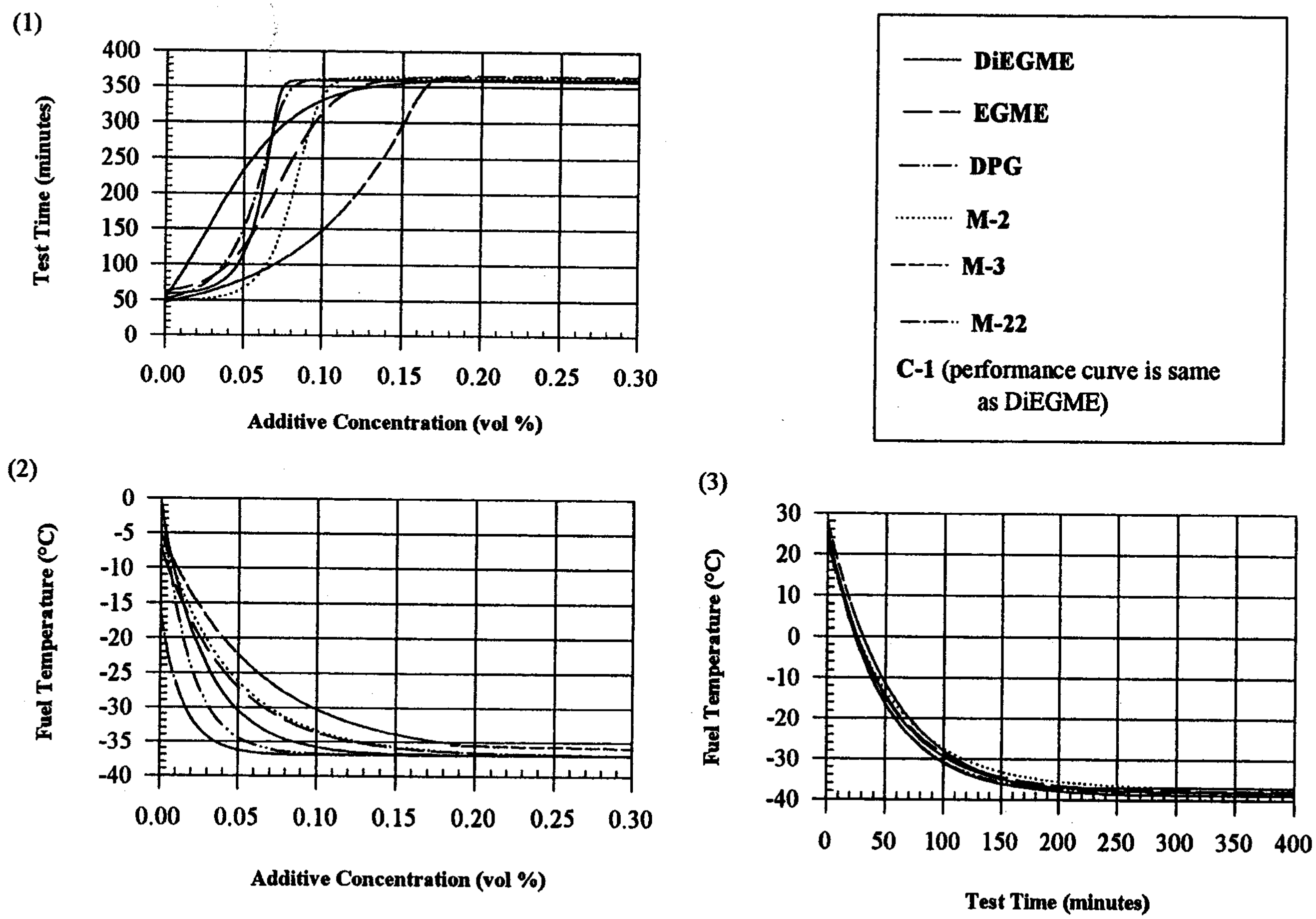
3. Test Time vs. Fuel Temperature: an exponential decay of the form

$$\text{Temperature} = a + be^{-c(\text{Time})}$$

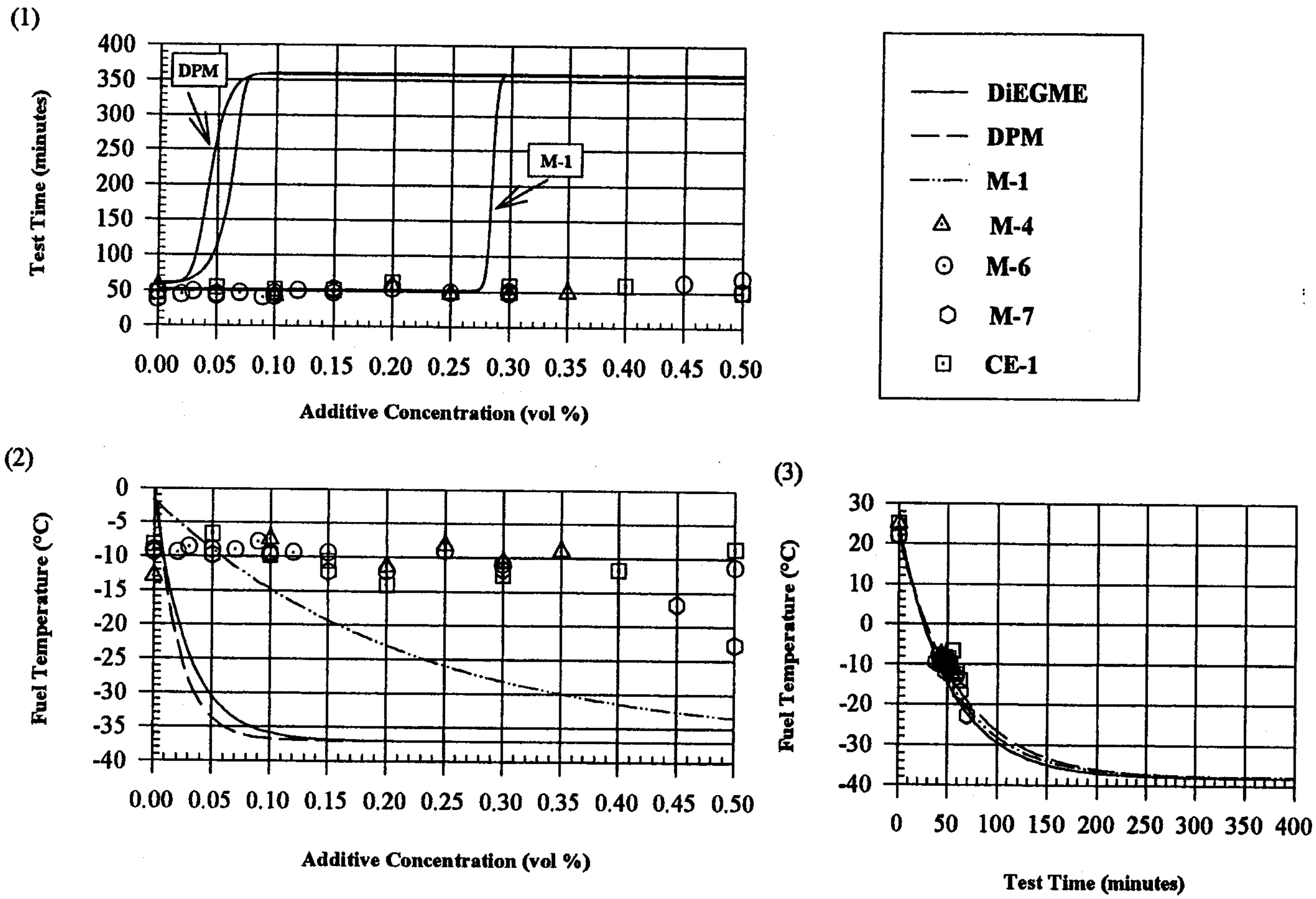
where

a = lowest temperature experienced (temperature is set so it goes no lower than -37 °C to -40 °C)
b = amplitude of curve (a + b = fuel temperature intercept)
c = rate constant

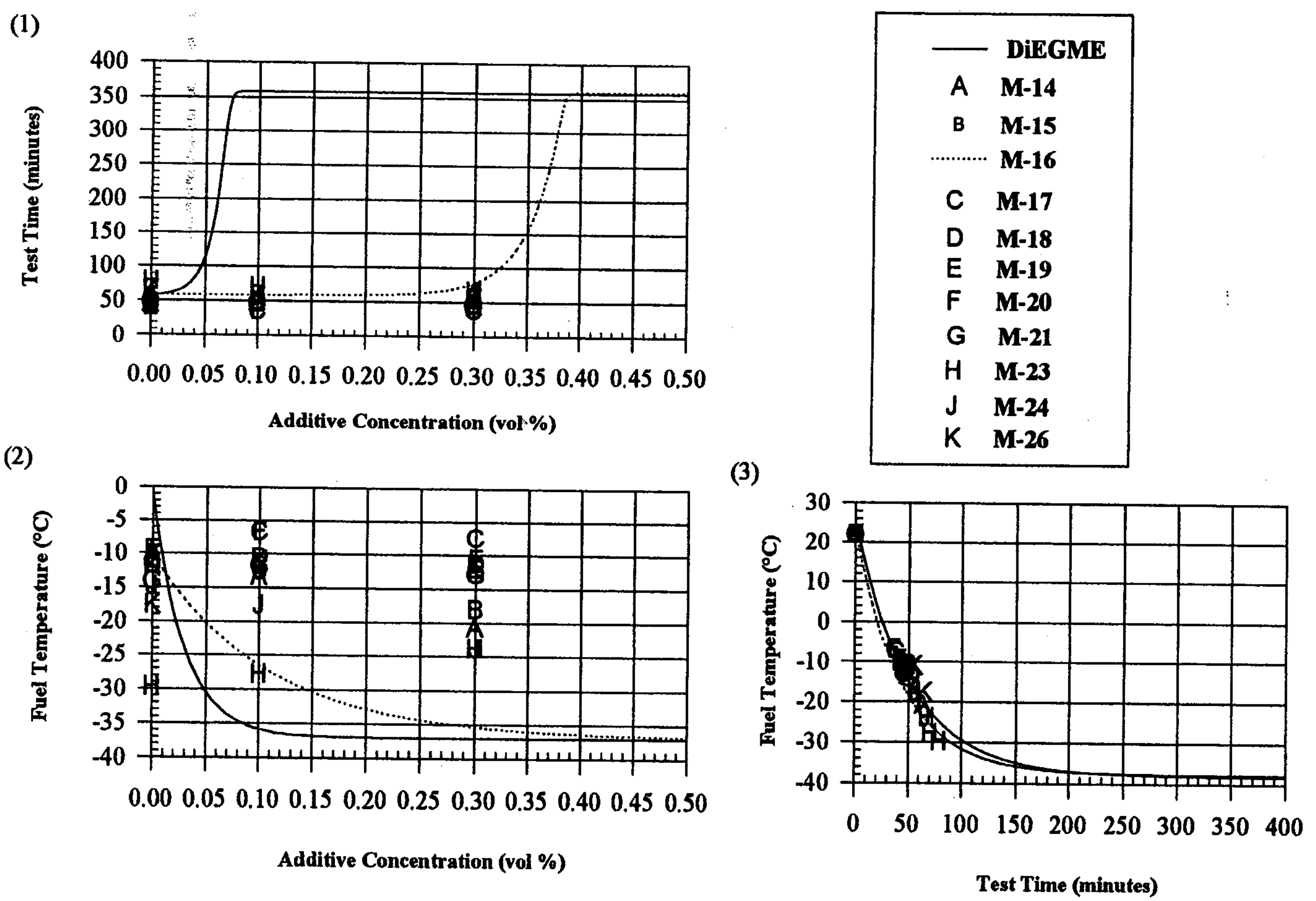
Performance Comparison of Successful FSII's/ Candidates for Additional Research



Performance Comparison of Candidates Not Selected for Additional Research (Part 1)



Performance Comparison of Candidates Not Selected for Additional Research (Part 2)



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